LIFE CYCLE INVENTORY OF FIVE PRODUCTS PRODUCED FROM POLYLACTIDE (PLA) AND PETROLEUM-BASED RESINS

TECHNICAL REPORT

Prepared For

ATHENA INSTITUTE INTERNATIONAL

By

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FOREWORD

The focus of this report is on comparative life cycle inventory (LCI) results for the production of various kinds of plastic consumer products made from petroleum- and bio-based resins. The Athena Institute was pleased to have the opportunity to commission the work because we have long been concerned about the general tendency to identify environmentally preferable products or processes solely on the basis of specific attributes. While there is often an intuitively appealing basis for claims about recycled content, renewability, or the relative merits of bio-based products, the claims do not always stand up to objective analysis. In some cases it depends on the situation, and in other cases on how comprehensively we examine the relative effects. Life cycle assessment is the method by which we can more fully assess the environmental effects associated with products and processes, and better understand the trade-offs that may be implicit in purchasing or production decisions.

There is an intuitive appeal of plastics made from a bio-based resin such as NatureWorks® PLA, made from corn grain, versus those made from petroleum-based resins. Fossil fuel depletion is certainly a major concern for society; it is in fact one of the key environmental impact measures used in LCA. So even though the production of hydrocarbon-based polymers uses only approximately 3% of the oil and natural gas extracted each year, it seems reasonable to applaud and support any substitution of a hydrocarbon product with one derived from agriculture. However, intensive cropping (especially with irrigated crops) depletes the soil and we must equally be concerned about the degradation of cropland as a natural resource. We should also be cognizant of the implications of using food crops to make consumer products, thereby diverting land from growing food for a relentlessly growing world population. As well, there is a rapidly growing demand for corn to be used in the manufacture of ethanol, another means by which we can reduce our dependence on fossil fuels. It's important to ask which of these competing uses of cropland will have a more beneficial environmental effect.

One could also cite considerations such as the possible requirement for more water or the use of ancillary materials such as nitrogen fertilizer, pesticides and herbicides to grow corn as compared to many other crops. The point is that all of these factors are relevant to any comparison and we have to bring as much science and objectivity to bear on the decisions as possible. We also have to exercise care to include all of the life cycle activities necessary for the manufacture, use, and disposal of final products, and not focus on just the production of a particular material.

At the disposal end of the life cycle, we again encounter tendencies to highlight potential environmental benefits that don't necessarily match reality in terms of what is currently happening or possible. For example, when conventional plastics are placed in a landfill, excavation data shows that they degrade very slowly, if at all, in a 100-year time frame. While this isn't positive from a landfill capacity perspective, it does mean that carbon is sequestered and air and water pollution is minimized. While some bio-based plastics are biodegradable, we really don't know what will happen when these bio-based plastics are placed in a landfill because there is very little relevant data. Dr. Rathje's

University of Arizona Garbage Project landfill excavation data shows that readily degradable paper does not actually degrade quickly in the landfill environment; 50-year-old newspapers from landfills were still perfectly readable. If it does degrade anaerobically, the data for paper products indicates that the resulting site-dependent emissions may include methane, carbon dioxide or more complex chemicals. The fact is that claims about the biodegradability benefits of bio-based plastics are in the realm of conjecture until we have more experience and data.

A similar problem of inadequate data prevails when we look at other end-of-life possibilities. For example, PLA can be composted if a community has a composting facility, while most conventional plastics cannot. But some report that PLA degrades only with difficulty, and will not degrade in a home composting project, which means reliance on a commercial operation. Again, we simply don't know enough at this stage. If we look at incineration of solid waste, the merits of PLA are more apparent. Conventional plastics produce carbon dioxide, water and lower levels of other compounds if the incineration is conducted in an optimum manner. If not, the combustion products may contain carbon monoxide and possibly other toxic emissions. The carbon emissions increase the level of greenhouse gases in the atmosphere. If PLA is incinerated, the same results could be expected as for conventional plastics. A major difference, however, is that the carbon is of biomass origin, so its return to the atmosphere is part of a natural cycle and would not be viewed as a contribution to increased greenhouse gases.

Recycling is especially notable because conventional plastics can be recycled, although the levels of recycling are often not very high. PLA is theoretically recyclable, but there are not sufficient products in the market to test the feasibility of routine recycling. The reality in this case is that PLA cannot be mixed with other plastics for recycling, so networks specifically aimed at PLA are necessary. In fact, if PLA bottles are mixed with PET bottles, they have the potential to harm the existing extensive PET recycling infrastructure because of the incompatibility of the two materials. This is not to say that we shouldn't encourage the development of appropriate infrastructure and work toward a day when all kinds of plastics can be routinely recycled. But we have to be cautious that we don't lose more than we gain in the shorter term.

In general, then, the world of plastics is no less complex than any of the other environmental issues that we face. There are no simple, black and white answers. While this report doesn't cover all of the issues to the same extent, or to the degree that may be warranted, it does provide hard data on the environmental flows associated with comparable plastic products made from bio-based and petroleum-based resins. We trust that it will help shift the discussion from a fairly simplistic focus on attributes toward a more scientific and objective analysis of true environmental performance. As readers will see from the results presented here, there is no clear winner in this comparison; there is an identification of trade-offs, which is as it should be.

Wayne Trusty
President, Athena Institute
November 2006

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LIFE CYCLE INVENTORY OF FIVE PRODUCTS PRODUCED FROM PLA AND PETROLEUM-BASED RESINS TECHNICAL REPORT

1. INTRODUCTION

This is the detailed technical report on a Life Cycle Inventory (LCI) of five products — 16-ounce cups, two-piece 16-ounce deli containers, envelope window film, foam meat trays, and 12-ounce water bottles — produced from corn-based polylactide (PLA) and various petroleum-based resins. Most of the PLA products are already in the marketplace. The results of this study can be used to evaluate the environmental footprint of these five products.

This study was conducted for Athena Institute International by Franklin Associates, a Division of ERG, as an independent contractor. At Franklin Associates, the project was managed by Melissa Huff, who served as primary life cycle analyst in researching, analyzing results, and developing the report. James Littlefield assisted with modeling, review, and editing. Beverly Sauer also provided a quality assurance review of the report. William E. Franklin provided overall project oversight as Principal in Charge.

GOAL, SCOPE, AND BOUNDARIES

The principal goal of this study is to evaluate the energy and emissions associated with the production and disposal of various products made from PLA resin and petroleum-based plastic resins currently and soon to be in the market, in order to develop a better understanding of the key factors affecting their environmental profiles. The focus is on comparing actual products using PLA and petroleum-based resins, as opposed to comparing resins on a weight basis; the latter is misleading because different products from different resins have diverse weights, and product weight is a key factor in the analysis. In order to make meaningful comparisons of product systems, the resin basis weight data must be multiplied by the appropriate weighting factors to reflect their use in a defined product and then combined to model a product system on an equivalent use basis.

This analysis includes the following four steps for each product:

1. Production of the product materials, which includes all steps from the extraction of raw materials through the production of the product resins.
2. Transportation of the product resins to fabrication.
3. Fabrication of the products from their resins.
4. Post consumer disposal of the products, including landfill and combustion of mixed municipal solid waste (MSW).

Transportation of the fabricated product, printing, and use of the product by consumers are assumed to be equivalent for all resin systems within each product category studied and are not included in this study. Environmental emissions associated with end-of-life management of the products are not part of the scope of this analysis.

Only landfilling and combustion of the products are analyzed for end-of-life management. Other end-of-life scenarios are possible for most of the products, but the other scenarios are relatively insignificant and we have focused on those that are more relevant.

LCI METHODOLOGY

The methodology used for goal and scope definition and inventory analysis in this study is consistent with the methodology for Life Cycle Inventory (LCI) as described in the ISO 14040 and 14044 Standard documents. A life cycle inventory quantifies the energy consumption and environmental emissions (i.e., atmospheric emissions, waterborne wastes, and solid wastes) for a given product based upon the study scope and boundaries established. However, the study departs from being a strict LCI by including a calculation of global warming potential (GWP) effects for the various products. The global warming potentials used in this study were developed in 2001 by the International Panel of Climate Change (IPCC). The 100 year GWP used are as follows: fossil carbon dioxide -1, methane - 23, nitrous oxide - 296, CFC/HCFCs - 1700, methylene chloride - 10, HCFC22 - 1700. Otherwise, this is a cradle-to-grave LCI analysis, covering steps from raw material extraction through product disposal.

The five products can be manufactured using PLA resin and various petroleum-based resins. No secondary packaging is considered in this analysis; only the primary product is analyzed. Flow diagrams of the resins and the total life-cycle systems are shown for each of the products in the detailed technical report.

Typical life cycle inventory data is available based on a given weight of a plastic resin, aluminum, steel, etc. Consumers do not use a pound of aluminum; for example, they use an aluminum can and it is therefore important to take the weight-based data and translate it into actual products that the public uses. It is for this reason that the five common items were selected.

SYSTEMS STUDIED

The drink cups in this analysis are 16-ounce cold drink cups. Common resins for this cup include high-impact polystyrene (HIPS), polyethylene terephthalate (PET), and polypropylene (PP). The weight data for the cups in this analysis, including PLA, were provided by one company that produces all the types of cups studied.

The deli containers in this analysis are 16-ounce two-piece deli containers. However, two types of deli containers are considered in this analysis: a lightweight deli container used more commonly for hand-packing (PLA and general purpose polystyrene (GPPS)) and a heavier-weight deli container used more commonly for automated packing (PLA and PET). Two companies provided samples, which were weighed by Franklin Associates staff. One company provided lightweight deli containers of both PLA and GPPS, while the other provided heavier-weight deli containers of both PLA and PET. The deli container weights include both the container and flat lid.

The envelope windows are a standard gauge of 0.115 (1.15 mil). Weights for the envelope windows in this analysis were taken from the Alcoa Kama website for GPPS and from the Plastic Suppliers website for PLA.

The foam meat tray (#2 size) is the only product in this analysis where PLA is not already established in the market. Trials are being performed on PLA foam to be used for meat trays by various manufacturers. NatureWorks, LLC, the producer of NatureWorks® PLA resin, was consulted along with other experts in foaming technology and it was estimated that the PLA foam meat tray is five percent heavier than the corresponding polystyrene foam (GPPS foam) meat tray. Weights for the GPPS foam meat tray were provided by one company.

The final product analyzed is the 12-ounce water bottle. The main resin used for water bottles is PET. Samples were purchased and weighed by Franklin Associates staff. The PLA water bottle weights were provided by a bottle producer.

The weights of all products studied are shown in Table 1-1. In order to express the results on an equivalent basis, a functional unit of equivalent consumer use was chosen for four of the five products in this analysis.

- 16-ounce cold cups—10,000 cups
- 16-ounce two-piece deli containers—10,000 deli containers
- Foam meat trays—10,000 meat trays
- 12-ounce water bottles—10,000 water bottles

The envelope window film comparison is based on an equivalent area and gauge (1,000,000 square inches for a gauge of 0.115).

DATA SOURCES, LIMITATIONS AND ASSUMPTIONS

Although PLA resin is readily available in North America, Europe, and Asia, it was assumed that the majority of processes for the life cycles of the products occur in the United States. To make this report as transparent as possible, only publicly available data were used for the resins and product fabrication processes. The PlasticsEurope database was used for the petroleum-based resins as well as the fabrication of the products because there is not yet a publicly available database in the United States for these resins. Dr. Erwin Vink provided a journal paper, currently under peer review, that included NatureWorks 2005 and 2006 PLA data. Jim Nangeroni of NatureWorks provided information on the fabrication of PLA resin into products. Various contacts at product fabrication facilities also provided product fabrication information and product weights.

In the 2006 update, NatureWorks reports that as of January 2006 they had purchased wind power derived renewable certificates to offset their entire requirement for electricity at their Nebraska facility. There are large differences in the 2005 versus 2006 PLA datasets as a result of the credit given for this purchase of wind energy vouchers (e.g., a reduction of 33% in the life cycle requirement for non-renewable energy as

Table 1-1

WEIGHTS FOR VARIOUS PRODUCT APPLICATIONS FOR PLA AND PETROLEUM-BASED PLASTIC PRODUCTS

Products	Weight per unit		Weight per functional unit	
	(oz)	(g)	(lb)	(kg)
16-ounce cold drink cup (Basis: 10,000 cups)				
PLA	0.52	14.8	326	148
HIPS	0.43	12.3	271	123
PET	0.56	15.8	348	158
PP	0.37	10.5	231	105
Clear 16-ounce 2-piece deli container (Basis: 10,000 2-piece containers) (1)				
Light-Weight (2)				
PLA	0.63	18.0	396	180
GPPS	0.52	14.9	328	149
Heavy-Duty (2)				
PLA	0.71	20.0	441	200
PET	0.90	25.6	564	256
Envelope window film (Basis: 1,000,000 sq. inches)				
PLA			51.9	23.6
GPPS			43.5	19.7
Foam meat tray (Basis: 10,000 trays) (3)				
PLA Foam	0.19	5.5	121	54.8
GPPS Foam	0.18	5.2	115	52.2
12-ounce water bottle (Basis: 10,000 bottles)				
PLA	0.74	21.0	463	210
PET	0.72	20.3	448	203

(1) This weight includes both the container and a flat lid. Samples of lids and containers were weighed and averaged separately, then the averages were summed.
(2) Light weight deli containers are packed by hand, while heavy duty deli containers are filled using automated packing. The PET resin is commonly used for the automated packing, while the GPPS is commonly used for hand packing.
(3) This foam meat tray is commonly used for 1 pound packs of ground beef.

Source: Franklin Associates, a Division of ERG

compared to a 2005 baseline). However, NatureWorks does not access this wind power directly; certificates purchased on an open market help finance added wind power capacity that results in reduced dependence on fossil fuels. Any manufacturer of resin can buy these same certificates and achieve equivalent results. Since the conventional polymers data used in this report are generic rather than brand-specific, it is not possible to credit any such purchases by individual companies and it would therefore be misleading to credit the NatureWorks PLA. Moreover, LCI is an environmental decision making tool that accounts for the actual material and energy flows of a product or system; the inclusion of wind energy credits would be a departure from this goal. In view of the foregoing, only the 2005 PLA datasets were used in this analysis.

Franklin Associates staff estimated the energy for the drying of PLA resin, a hygroscopic resin, from specifications found on ConAir’s website for the dehumidifying dryer, CD1600. Transportation from the resin producer to the product fabrication was estimated using average distances between various locations of actual U.S. resin plants and product fabrication plants. The disposal of the products includes landfilling of post consumer products, as well as a 20 percent waste-to-energy (WTE) combustion energy credit for the incineration of post consumer products in mixed municipal solid waste. The Franklin Associates LCI models were used to calculate fuel production and delivery energy

and emissions for drying, resin transportation, and disposal steps. There may be small differences between the Franklin Associates model and the PlasticsEurope model.

To provide uniformity among the LCI results, atmospheric and waterborne emissions from the Franklin Associates fuel emissions model were limited to the emissions used in the PlasticsEurope database for consistency in reporting. A common practice in the PlasticsEurope database is the use of “<1” for emissions with less than 1 mg of emission per kg of product. In this analysis, the value “1” represents all “<1” values given by PlasticsEurope. This is the upper limit of these values, and so some emissions values may be overstated by an unknown amount.

REPORT STRUCTURE

The remainder of this report is structured so that each chapter deals with the LCI for one of the five products studied. Basic methodological and background information is provided in Chapter 1, with product-specific methodological or data information provided in the relevant chapters. The individual product chapters also present some repetitious methodological information that we felt should be presented each time in the context of the product specific information to ensure full understanding. Readers interested in individual products, as opposed to the full range, can essentially read a stand-alone product report by combining this introductory Chapter with any Chapter of interest. The three appendices provide more detail on data sources and methodological issues (Appendices A and B) , data quality (Appendix C) and the interpretation of results (Appendix D).

CHAPTER 2

ENERGY AND ENVIRONMENTAL RESULTS FOR 10,000 16-OUNCE COLD DRINK CUPS

INTRODUCTION

This chapter focuses on 16-ounce cold drink cups. Four plastic resins currently used in the marketplace for these drink cups were modeled: PLA (polylactide), HIPS (high-impact polystyrene), PP (polypropylene), and PET (polyethylene terephthalate).

In order to express the results on an equivalent basis, 10,000 16-ounce cold drink cups was selected as the functional unit of equivalent consumer use in this analysis. One company that produces cups from all resin types considered in this analysis (including PLA) provided the weight data for the 16-ounce cold drink cups. The weights of all 16-ounce cold drink cups are displayed in Table 1-1 of the Introduction. Figures 2-1 through 2-4 display flow diagrams of the production of the four resins analyzed in this analysis. Figure 2-5 shows the overall life cycle of the cups analyzed in this report.

No secondary packaging is considered in this analysis; only the primary product is analyzed. Environmental burdens associated with end-of-life management of the cups are not part of the scope of this analysis. Only landfilling and combustion of the cups are analyzed for end-of-life management.

ASSUMPTIONS AND LIMITATIONS

Key assumptions of the LCI of cold drink cups are as follows:

- All weight data for the cups were taken from one cup producer. Drink cup weights will vary by producer.
- The following distances and modes were used for each resin type:
  - PLA—560 ton-miles by combination truck
  - HIPS—157 ton-miles by combination truck, 157 ton-miles by rail
  - PP—325 ton-miles by combination truck, 325 ton-miles by rail
  - PET—94 ton-miles by combination truck, 95 ton-miles by rail
- The disposal of the products includes landfilling of post consumer products, as well as a 20 percent waste-to-energy (WTE) combustion energy credit for the incineration of post consumer products in mixed municipal solid waste. Although it is true that most of the petroleum-based plastic can be recycled and PLA is available for composting, only a very small percentage of cups will actually get into the recycling and composting streams.
- The higher heating values used for the resins analyzed in this chapter are PLA—19 MJ/kg, PET—26 MJ/kg, HIPS—40.3 MJ/kg, and PP—44.3 MJ/kg.

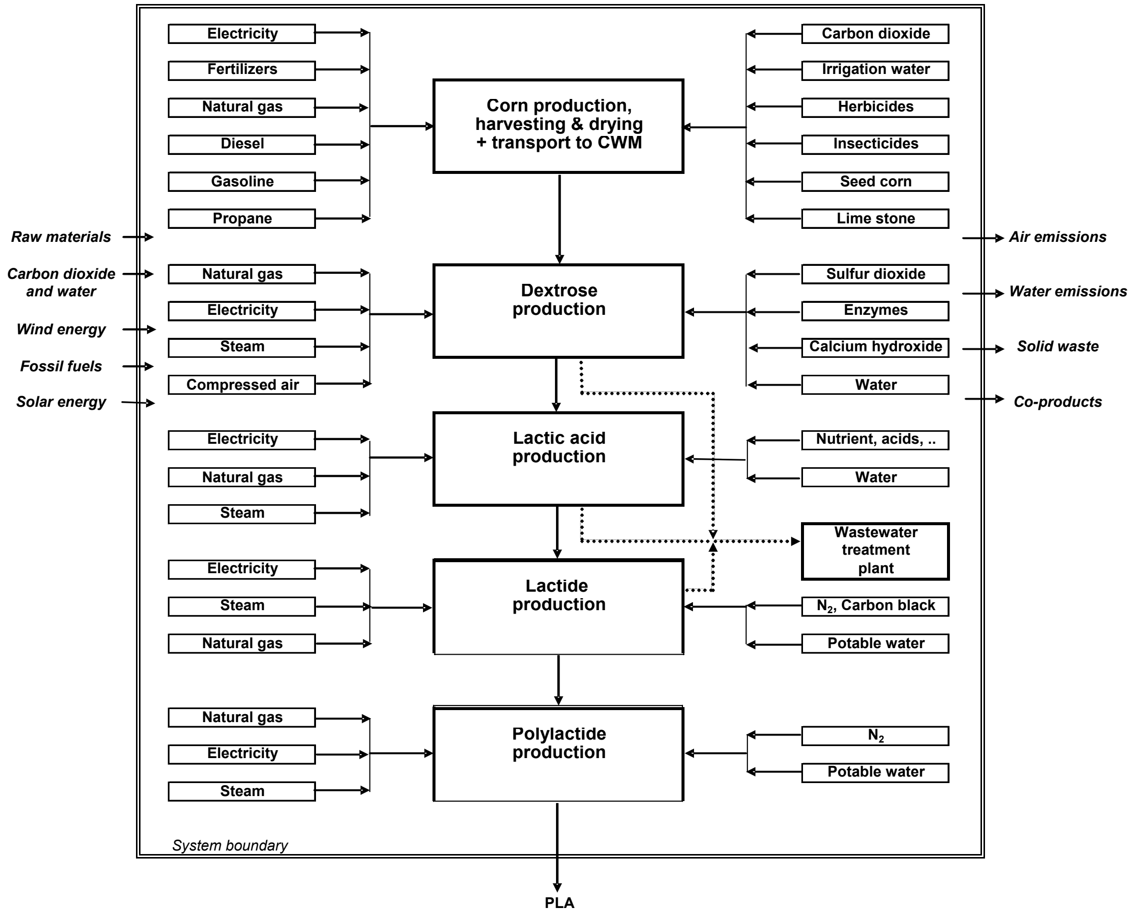

Figure 2-1. Simplified flow diagram and system boundary for the NatureWorks PLA resin production system. This flow diagram was taken from the 2006 draft journal paper provided by Dr. Erwin Vink of NatureWorks, LLC.

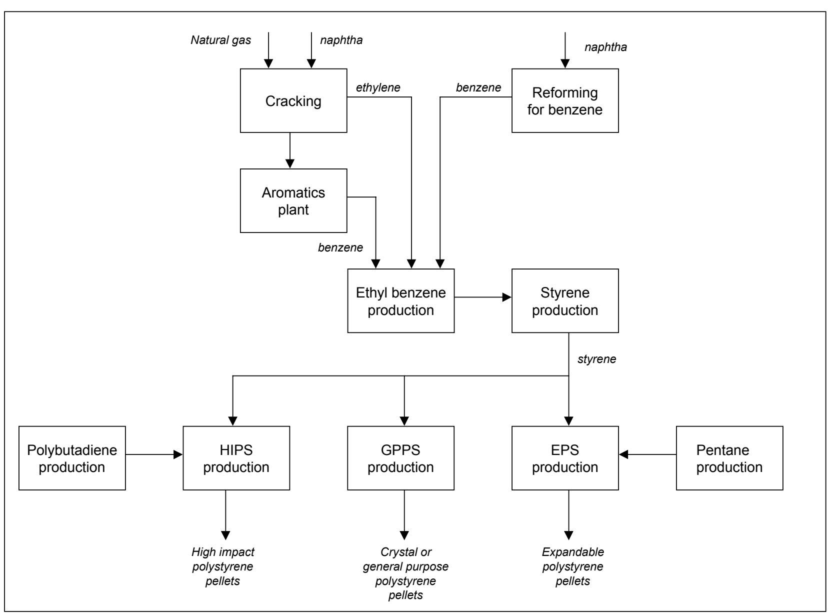

Figure 2-2. Flow diagram for the production of polystyrene resins. This flow diagram was taken from the report, Eco-profiles of the European Plastics Industry: Polystyrene (High-Impact) (HIPS), PlasticsEurope, updated June, 2005.

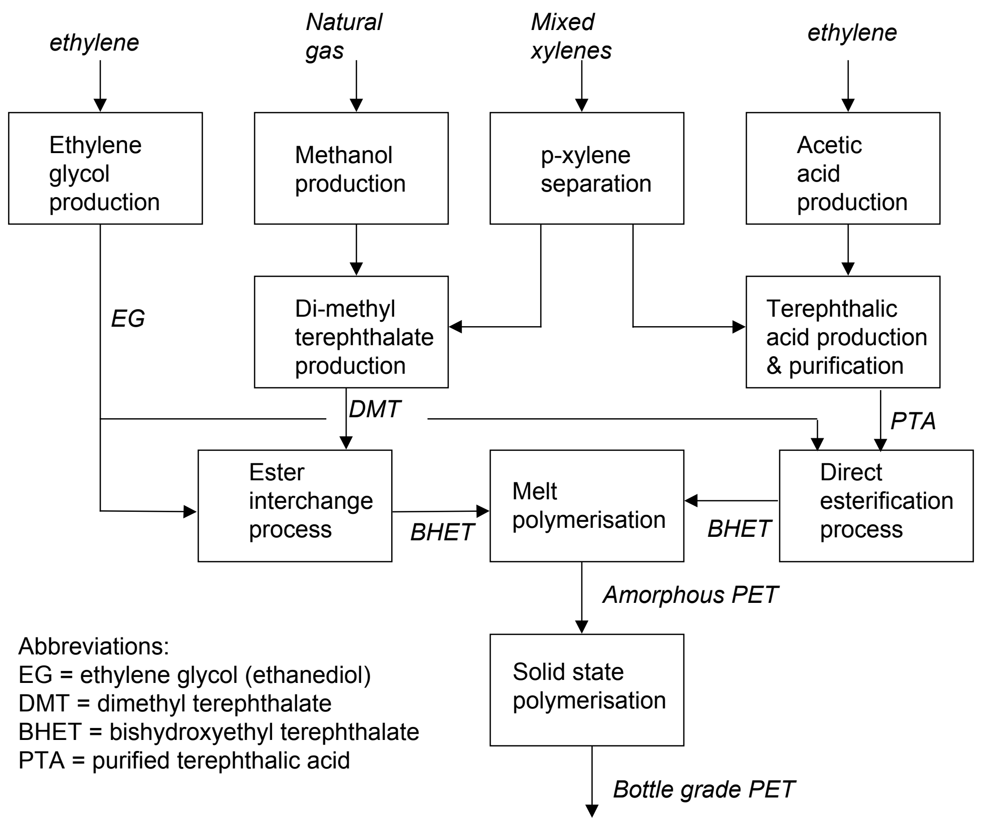

Figure 2-3. Flow diagram showing the two routes to polyethylene terephthalate (PET) resin. This flow diagram was taken from the report, **Eco-profiles of the European Plastics Industry: Polyethylene Terephthalate (PET) (Bottle grade)**, PlasticsEurope, updated March, 2005.

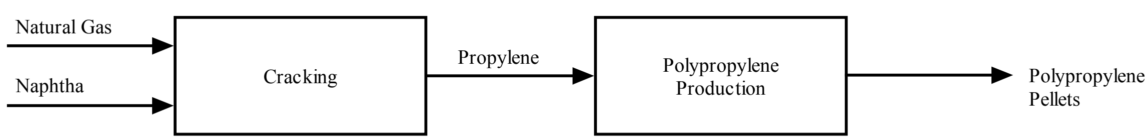

Figure 2-4. Flow diagram for the production of polypropylene resin.

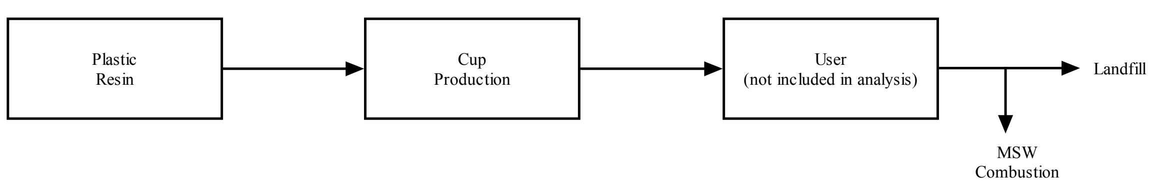

Figure 2-5. Flow diagram of the life cycle of 16-ounce disposable cold drink cups. Transportation to user and use phase are not included in this analysis.

RESULTS

If the energy or post consumer solid waste of one system is 10 percent different from another, it can be concluded that the difference is significant. If the weight of industrial solid waste, atmospheric emissions or waterborne emissions of a system is 25 percent different from another, it can be concluded that the difference is significant. Percent difference is defined as the difference between two values divided by the average of the two values. (See Appendix D for an explanation of this certainty range.)

Energy Results

The energy results separated into cradle-to-material and fabrication-to-grave categories are shown in Tables 2-1 and 2-2. The total energy for each cup in Table 2-1 is also separated into fuel production and delivery, energy content of delivered fuel, fuel use in transport, and feedstock energy. Table 2-1 also has a column that shows an energy credit for the energy recovered from waste-to-energy incineration of 20 percent of the post consumer solid waste. Table 2-2 breaks the total energy into fossil and non-fossil fuel.

The categories used for the breakdown of the total energy are used in the PlasticsEurope database. The following definitions are quotes from the Methodology report for the PlasticsEurope database. "*Energy content of delivered fuel* represents the energy that is received by the final operator who consumes energy. *Feedstock energy* represents the energy of the fuel bearing materials that are taken into the system but used as materials rather than fuels. *Transport energy* refers to the energy associated with fuels consumed directly by the transport operations as well as any energy associated with the production of non- fuel bearing materials, such as steel, that are taken into the transport process. *Fuel production and delivery energy* represents the energy that is used by the fuel producing industries in extracting the primary fuel from the earth, processing it and delivering it to the ultimate consumer." More information on these categories can be found in the Methodology report at PlasticsEurope's website: http://www.lca.plasticseurope.org/methodol.htm.

The PLA resin (cradle-to-resin) requires 79 percent of the total energy needed to make the 16-ounce drink cups, whereas the resin transportation, drying, thermoforming, and disposal require 21 percent of the total energy. The energy content of delivered fuel category requires the greatest amount of energy for the PLA cups. It makes up 40 percent of the PLA cups' total energy requirements. Although the feedstock energy category makes up 26 percent of the total energy for PLA, much of this feedstock energy represents the corn used as raw material. It is true that corn is used as a fuel (ethanol), but less than 7 percent of the corn grown in the U.S. in 2001 was used for fuel. The fuel use in transport energy makes up 5 percent of the PLA cup total energy.

Table 2-1

Energy by Category for 16-ounce Cold Drink Cups
(MJ per 10,000 16-ounce cold drink cups)

	Energy Category						
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit	Net Energy
16-ounce cold drink cup							
PLA (2005)							
Cradle-to-material	2,766	4,571	269	3,779	11,384		
Fabrication-to-Grave	1,406	1,259	406	0	3,072		
Total	4,172	5,830	675	3,779	14,456	562	13,893
HIPS							
Cradle-to-material	853	4,241	188	5,818	11,099		
Fabrication-to-Grave	1,135	882	182	0	2,199		
Total	1,988	5,122	370	5,818	13,299	1,029	12,270
PP							
Cradle-to-material	579	1,579	65.3	5,633	7,857		
Fabrication-to-Grave	980	753	231	0	1,964		
Total	1,560	2,332	296	5,633	9,821	852	8,969
PET							
Cradle-to-material	2,192	4,643	85.4	6,408	13,328		
Fabrication-to-Grave	1,451	1,133	191	0	2,775		
Total	3,643	5,776	276	6,408	16,103	964	15,139

	Energy Category (percent)					
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit
16-ounce cold drink cup						
PLA (2005)						
Cradle-to-material	19%	32%	2%	26%	79%	
Fabrication-to-Grave	10%	9%	3%	0%	21%	
Total	29%	40%	5%	26%	100%	4%
HIPS						
Cradle-to-material	6%	32%	1%	44%	83%	
Fabrication-to-Grave	9%	7%	1%	0%	17%	
Total	15%	39%	3%	44%	100%	8%
PP						
Cradle-to-material	6%	16%	1%	57%	80%	
Fabrication-to-Grave	10%	8%	2%	0%	20%	
Total	16%	24%	3%	57%	100%	9%
PET						
Cradle-to-material	14%	29%	1%	40%	83%	
Fabrication-to-Grave	9%	7%	1%	0%	17%	
Total	23%	36%	2%	40%	100%	6%

Source: Franklin Associates, a Division of ERG

Using the percent difference calculation as described above, the following conclusions can be made about a comparison of the total energy requirements of 16-ounce cold drink cups. The PET cup requires the most total energy, while the PP cup requires the least total energy. This correlates with the fact that the PET cup is the heaviest, while the PP cup is the lightest. The PLA 2005 cup requires significantly more energy than the PP cup and less than the PET cup; however, it is not significantly different than the HIPS cup.

Also included in Table 2-1 is the energy recovered from the combustion of 20 percent of post consumer cups that are discarded, based on the national average percentage of municipal solid waste that is disposed by waste-to-energy (WTE) combustion[1]. These are calculated using the higher heating value of the resin used multiplied by 20 percent of the weight of the cups disposed. The higher heating value (HHV) of PLA is less than the petroleum-based resins; therefore, less combustion energy credit is given to the PLA cups. The HHV for each resin is found in the Assumptions and Limitations section of this chapter. If combustion energy credit is given, the net energy conclusions do differ from the total energy conclusions regarding the PLA cups. The PLA 2005 cup requires significantly more energy than the PP and HIPS cups and is not significantly different from the PET cup.

Table 2-2 shows the fuel sources of cradle-to-production energy by fossil and non-fossil fuel for 10,000 16-ounce cold drink cups. All four categories shown in Table 2-1 are included in the total energy results shown in the table. The fossil fuels include natural gas, petroleum and coal. These fuels are commonly used for direct combustion for process fuels and generation of electricity. Natural gas and petroleum are also used as raw material inputs for the production of petroleum-based plastics. Petroleum is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear, biomass, wind, and other (geothermal, etc.) shown in the table are used to generate electricity along with the fossil fuels. It should be noted that corn as feedstock energy is considered biomass and therefore in the non-fossil fuel.

The PLA cup requires 65 percent fossil fuel use, with the remainder coming from non-fossil sources. This is due to the feedstock energy, which is from corn, a non-fossil source. The petroleum-based plastic cups require greater than 90 percent fossil fuel use. The feedstock energy of the petroleum-based plastic cups makes up between 44 and 62 percent of the fossil fuel required for those cups.

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1 **Municipal Solid Waste in the United States: 2001 Facts and Figures.** U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. August 2003.

Table 2-2

Energy by Fuel Type for 16-ounce Cold Drink Cups
(MJ per 10,000 16-ounce cold drink cups)

	Fuel Type			Fuel Type (percent)		
	Fossil Fuel	Non-fossil Fuel	Total	Fossil Fuel	Non-fossil Fuel	Total
16-ounce cold drink cup						
PLA (2005)						
Cradle-to-material	6,903	4,480	11,384	48%	31%	79%
Fabrication-to-Grave	2,473	599	3,072	17%	4%	21%
Total	9,376	5,079	14,456	65%	35%	100%
HIPS						
Cradle-to-material	10,685	414	11,099	80%	3%	83%
Fabrication-to-Grave	1,736	463	2,199	13%	3%	17%
Total	12,422	877	13,299	93%	7%	100%
PP						
Cradle-to-material	7,512	345	7,857	76%	4%	80%
Fabrication-to-Grave	1,568	396	1,964	16%	4%	20%
Total	9,080	741	9,821	92%	8%	100%
PET						
Cradle-to-material	12,456	872	13,328	77%	5%	83%
Fabrication-to-Grave	2,181	594	2,775	14%	4%	17%
Total	14,637	1,466	16,103	91%	9%	100%

Source: Franklin Associates, a Division of ERG

Solid Waste

Solid waste details separated into cradle-to-material and fabrication-to-grave categories are shown in Table 2-3. Solid waste is categorized into empirical categories, following the methodology of the PlasticsEurope database. According to the PlasticsEurope methodology report, “In the empirical system, the aim is to categorize solid waste into the smallest number of different categories that identify the type of disposal that has to be applied or the use, if any, to which the waste can be put after appropriate processing”. Also included in the solid waste table are post consumer wastes, which are the wastes discarded by the end users of the product.

No solid waste data were provided in Dr. Vink’s journal paper for the PLA 2005 resin. The solid waste data shown for the PLA resin in Table 2-3 are estimated from the PLA (2006) dataset and do not include the solid waste credited for the purchase of wind energy credits. In many of the categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.

Post consumer wastes are the wastes discarded by the final users of the product. As we are including the U.S. average combustion of mixed municipal solid waste, 20 percent of that weight is combusted in waste-to-energy facilities and therefore subtracted out of the total post consumer wastes. The weight of post consumer wastes is directly related to the weight of a product. Therefore, heavier products produce more post consumer solid wastes. For the 16-ounce cold drink cups, the PET cup is the heaviest and so produces the most post consumer solid waste; however, the PLA cup post consumer solid waste is not considered significantly different than the PET cup (see Appendix D for an explanation of the certainty range). The PLA and PET cups are heavier than the cups made from PP and HIPS and produce a significantly greater amount of post consumer solid waste.

Table 2-3

Solid Wastes for 16-ounce Cold Drink Cups
(g per 10,000 cold drink cups)

	PLA (2005)			HIPS			PP			PET		
	Cradle-to-PLA resin	Fab-to-Grave	Total (1)	Cradle-to-HIPS resin	Fab-to-Grave	Total	Cradle-to-PP resin	Fab-to-Grave	Total	Cradle-to-PET resin	Fab-to-Grave	Total
Solid Waste Categories												
Plastic containers	0	0	0	0.13	0	0.13	0.11	0	0.11	0.16	0	0.16
Paper	0	4,413	4,413	0.13	3,667	3,668	0.11	3,131	3,131	0.16	4,711	4,711
Plastics	151	83.1	234	12.2	69.0	81.2	36.4	58.9	95.3	371	88.7	459
Metals	0	2.07	2.07	10.3	1.72	12.0	0.11	1.47	1.57	0.16	2.21	2.37
Putrescibles	0	0	0	0.25	0	0.25	0.21	0	0.21	0.16	0	0.16
Unspecified refuse	159	602	761	314	501	814	99.6	427	527	242	643	885
Mineral waste	2,781	515	3,296	226	428	654	22.5	365	388	64.5	550	614
Slags & ash	68.5	2,985	3,054	1,506	919	2,424	814	874	1,688	3,546	1,129	4,674
Mixed industrial	341	68.9	410	276	57.2	333	118	48.9	167	226	73.5	299
Regulated chemicals	667	74,634	75,302	52,693	62,027	114,720	182	52,950	53,132	451	79,677	80,128
Unregulated chemicals	171	410	581	464	341	805	203	291	494	1,434	438	1,872
Construction waste	0.30	0	0.30	9.28	0	9.28	0.21	0	0.21	8.70	0	8.70
Waste to incinerator	0	224	224	2,886	186	3,071	118	159	276	129	239	368
Inert chemical	0.15	119	119	339	99.2	438	86.8	84.6	171	306	127	434
Wood waste	0	41.7	41.7	0.13	34.6	34.7	0.11	29.6	29.7	0.16	44.5	44.6
Wooden pallets	0	2.24	2.24	0.13	1.86	1.99	0.11	1.59	1.70	0.16	2.39	2.55
Waste to recycling	0.15	26.8	26.9	52.7	22.2	74.9	171	19.0	190	29.0	28.6	57.6
Waste returned to mine	1.96	1,640	1,642	6,148	1,363	7,511	1,714	1,164	2,877	9,186	1,751	10,937
Tailings	1,468	0	1,468	866	0	866	26.8	0	26.8	0.48	0	0.48
Municipal solid waste	0	987	987	-401	820	419	-493	700	208	1,112	1,054	2,166
Postconsumer solid waste	0	118,400	118,400	0	98,400	98,400	0	84,000	84,000	0	126,400	126,400

(1) No solid waste data were provided in Dr. Vink's journal paper for the PLA(2005) resin. The data shown for the resin is estimated from the PLA(2006) dataset and does not include the solid waste credited for the purchase of wind energy credits.

Source: Franklin Associates, a Division of ERG

Environmental Emissions

Atmospheric and waterborne emissions for each system include emissions from processes and those associated with the combustion of fuels. Table 2-4 presents atmospheric emissions results and Table 2-6 shows waterborne emissions for 10,000 16-ounce cold drink cups. Table 2-5 gives a greenhouse gas summary for each of the cups analyzed. Atmospheric and waterborne emissions from the Franklin Associates fuel emissions model were limited to the emissions used in the PlasticsEurope database for consistency in reporting. A common practice in the PlasticsEurope database is the use of "<1" for emissions with less than 1 mg of emission per kg of product. In this analysis, the value "1" represents all "<1" values given by PlasticsEurope. This is the upper limit of these values, and so the values may be overstated by an unknown amount.

There are significant uncertainties with regard to the application of the data to the cup systems. Because of these uncertainties, two systems' emissions of a given substance are not considered significantly different unless the percent difference exceeds 25 percent. (Percent difference is defined as the difference between two system totals

divided by their average.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix D).

It is important to realize that interpretation of air and water emission data requires great care. The effects of the various emissions on humans and on the environment are not fully known. The degree of potential environmental disruption due to environmental releases is not related to the weight of the releases in a simple way. No firm conclusions can be made from the various atmospheric or waterborne emissions that result from the product systems. Only comprehensive tables of the atmospheric and waterborne emissions are shown here.

Atmospheric Emissions. The predominant atmospheric emissions from the product systems include greenhouse gases (particularly carbon dioxide, methane, and nitrous oxide), nitrogen oxides, sulfur oxides, particulates (PM10), and hydrocarbons. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different air emissions or groups of air emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, *methane*, *aromatic hydrocarbons* and *polycyclic hydrocarbons* have been identified as separate groups with the more general heading of *hydrocarbons* being reserved for the remainder. When such a split has been introduced, there is no double counting. For example, if a benzene emission is included in the *aromatics* group, it is not included in the more general category of *hydrocarbons*."

Table 2-4 displays the individual atmospheric emissions for each of the cup systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA datasets, where precise amounts were given. No firm conclusions can be made from the various atmospheric emissions that result from the drink cup systems.

Greenhouse Gases. This analysis is not an LCIA (life cycle impact assessment) and thus the impacts of various environmental emissions are not evaluated. However, due to our understanding of the relationship between greenhouse gases and global warming, it is reasonable to develop conclusions based on the quantity of greenhouse gases generated by a system. Greenhouse gas emissions are expressed as carbon dioxide equivalents, which use global warming potentials developed by the International Panel on Climate Change (IPCC) to normalize the various greenhouse gases to an equivalent weight of carbon dioxide. The 100-year time horizon Global Warming Potentials for GHG was used for this analysis.

Table 2-4

Atmospheric Emissions of 16-ounce Cold Drink Cups
(g per 10,000 cold drink cups)

	PLA (2005)	HIPS	PP	PET
Atmospheric Emissions				
dust (PM10)	1,504	177	109	372
CO	1,431	874	867	1,441
CO2	407,570	470,516	290,306	616,836
SOX as SO2	2,547	1,965	1,242	2,861
H2S	0.30	0.25	0.21	0.32
mercaptan	3.2E-04	0.13	0.11	0.16
NOX as NO2	2,868	1,217	847	1,768
NH3	0.95	0.21	0.22	0.25
Cl2	0.024	0.13	0.11	0.16
HCl	64.9	13.3	9.82	32.2
F2	1.5E-05	0.13	0.11	0.16
HF	2.77	0.51	0.33	1.29
hydrocarbons not specified elsewhere	495	595	544	1,568
aldehyde (-CHO)	0.41	0.30	0.33	0.34
organics	12.2	25.8	6.68	50.8
Pb+compounds as Pb	0.0014	0.13	0.11	0.16
Hg+compounds as Hg	2.8E-04	0.13	0.11	0.16
metals not specified elsewhere	0.70	0.86	0.63	1.11
H2SO4	0.0020	0.13	0.11	0.16
N2O	56.3	0.54	0.62	0.61
H2	25.8	11.7	6.23	27.1
dichloroethane (DCE) C2H4Cl2	3.0E-05	0.13	0.11	0.16
vinyl chloride monomer (VCM)	5.0E-04	0.13	0.11	0.16
CFC/HCFC/HFC not specified elsewhere	1.1E-06	0.13	2.46	0.16
organo-chlorine not specified elsewhere	1.51	0.13	0.11	0.16
HCN	0	0.13	0.11	0.16
CH4	3,709	4,561	2,188	4,404
aromatic HC not specified elsewhere	0.66	6.82	11.1	58.6
polycyclic hydrocarbons (PAH)	5.5E-05	0.50	0.11	1.13
NMVOC	74.3	25.3	22.4	218
CS2	0	0.13	0.11	0.16
methylene chloride CH2Cl2	0.0012	0.13	0.11	0.16
Cu+compounds as Cu	6.6E-05	0.13	0.11	0.16
As+compounds as As	0.0013	0.13	0.11	0.16
Cd+compounds as Cd	2.1E-04	0.13	0.11	0.16
Ag+compounds as Ag	0	0.13	0.11	0.16
Zn+compounds as Zn	3.4E-04	0.13	0.11	0.16
Cr+compounds as Cr	8.9E-04	0.25	0.11	0.64
Se+compounds as Se	0.0037	0.13	0.11	0.16
Ni+compounds as Ni	0.0059	0.50	0.11	1.13
Sb+compounds as Sb	9.5E-05	0.13	0.11	0.16

Table 2-4 (Cont'd)

Atmospheric Emissions of 16-ounce Cold Drink Cups
(g per 10,000 cold drink cups)

	PLA (2005)	HIPS	PP	PET
Atmospheric Emissions				
ethylene oxide C2H4O	0	0	0	0.16
ethylene C2H4	0	0.88	0.21	0.32
oxygen	0	0.13	0.11	0.16
asbestos	0	0.13	0.11	0.16
dioxin/furan as Teq	3.0E-07	0.13	0.11	0.16
benzene C6H6	0.13	2.28	0.14	0.35
toluene C7H8	0.18	0.53	0.15	0.19
xylenes C8H10	0.11	0.14	0.13	0.18
ethylbenzene C8H10	0.014	1.76	0.11	0.16
HCFC-22 CHClF2	0.14	0.25	0.10	0.15
styrene	3.3E-08	10.8	0.11	0.16
propylene	0.028	0.78	0.13	0.19
Fe+compounds as Fe	3.5E-04	0	0	0
Co+compounds as Co	6.3E-04	1.0E-04	1.3E-04	1.0E-04
V+compounds as V	0.0018	0	0	0
Al+compounds as Al	-0.62	0	0	0
B+compounds as B	7.7E-04	0	0	0
Lanthanides	0	0	0	0
Manganese	0.0019	2.0E-04	2.6E-04	2.1E-04
Molybdenum	1.5E-05	0	0	0
Corn dust	11.3	0	0	0
Tin	7.5E-05	0	0	0
Titanium	1.5E-05	0	0	0
Barium	0.053	0	0	0
Beryllium	6.2E-05	3.1E-06	4.0E-06	3.2E-06
Bromine	6.3E-04	0	0	0
Cyanide (unspecified)	1.4E-04	1.4E-07	1.8E-07	1.4E-07
Fluoride (unspecified)	2.6E-04	9.5E-06	1.2E-05	9.9E-06
Helium	0.058	0	0	0
VOC (volatile organic compou	0.037	0	0	0
Dust (PM 2.5)	2.25	0	0	0
Dust (unspecified)	21.2	1.34	1.72	1.39
Ethanol	68.7	0	0	0
Lactic acid	0.13	0	0	0
Particles (< 2.5 um)	-3.16	0	0	0
Particles (> 10 um)	-38.6	0	0	0
Particles (<10 and > 2.5 um)	-34.5	0	0	0

Source: Franklin Associates, a Division of ERG

Table 2-5

Greenhouse Gas Summary for 16-ounce Cold Drink Cups
(g carbon dioxide equivalents per 10,000 cold drink equivalents)

	PLA (2005)	HIPS	PP	PET
CO2	407,570	470,516	290,306	616,836
N2O	16,665	161	184	180
CFC/HCFC/HFC not specified elsewhere	0.0019	213	4,188	274
CH4	85,303	104,909	50,333	101,292
methylene chloride CH2Cl2	0.012	1.26	1.07	1.61
HCFC-22 CHClF2	246	418	175	263
Total	509,784	576,218	345,187	718,847

Note: The 100 year global warming potentials from 2001 used in this table are as follows: fossil carbon dioxide--1, nitrous oxide--296, CFC/HCFCs--1700, methane--23, methylene chloride--10, HCFC22--1700.

Source: Franklin Associates, a Division of ERG

Greenhouse gas emissions are closely related to system fossil energy, and thus the trends observed for system fossil energy requirements also apply to system greenhouse gas emissions. The PP cup produces the lowest amount of CO_2 equivalents. The PLA 2005 drink cup produces a significantly greater amount of CO_2 equivalents than the PP drink cup. This is due to the fact that much of the fossil fuel used in the PP drink cup is from feedstock energy, which is bound within the product and therefore does not produce greenhouse gases. There is no significant difference in GHG emissions between the PLA 2005 cup system and the HIPS cup system. The GHG emissions of the PLA 2005 cup system is significantly less than the PET cup system.

Waterborne Emissions. The predominant waterborne emissions from the container systems include dissolved solids, suspended solids, COD (chemical oxygen demand), BOD (biological oxygen demand), chlorides, and various metals. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different water emissions or groups of water emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, some specific metal ions are identified separately from the more general heading of metals. When such a split has been introduced, there is no double counting. For example, if a Na+ emission is identified, it is not included in the more general category of *metals (unspecified).* However, some operators may not necessarily have reported separately all of the metals specifically identified elsewhere in the table. As a consequence, the category *metals (unspecified)* may well include some metals that were specifically identified by other companies and are included under the appropriate specific heading elsewhere in the table."

Table 2-6 displays the individual waterborne emissions for each of the cup systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets.

This is not true of the PLA datasets, where precise amounts were given. No firm conclusions can be made from the various waterborne emissions that result from the drink cup systems.

CONCLUSIONS

A life cycle inventory (LCI) is an environmental profile that expresses environmental burdens from the perspective of energy consumption, solid waste generation, atmospheric emissions, and waterborne emissions. This LCI evaluated 16-ounce cold drink cup systems and found that three types of environmental burdens were helpful in distinguishing the LCI results: 1) energy requirements, 2) solid waste generation, and 3) greenhouse gas emissions. The LCI conclusions for each of these categories are summarized below.

Energy Requirements

- The PET cup requires the most total energy, while the PP cup requires the least total energy. This correlates with the fact that the PET cup is the heaviest, while the PP cup is the lightest.
- The PLA 2005 cup requires significantly more energy than the PP cup and less than the PET cup; however, it is not significantly different from the HIPS cup.
- If combustion energy credit is given, the net energy conclusions do differ (due to the different HHVs and weights of cup) from the total energy conclusions regarding the PLA cup as follows:
  - The PLA 2005 cup requires significantly more energy than the PP and HIPS cups and is not significantly different than the PET cup.
  - The petroleum-based plastic cups require more fossil fuel than the PLA cup. This is due in a large part to the feedstock energy of the petroleum-based plastic cups.

Solid Waste Generation

- In many of the empirical solid waste categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.
- For the 16-ounce cold drink cups, the PET cup is the heaviest and so produces the most post consumer solid waste; however, the PLA cup post consumer solid waste is not considered significantly different from that of the PET cup.
- The PLA and PET cups produce significantly more post consumer solid waste than the PP and HIPS cups.

Table 2-6

Waterborne Emissions of 16-ounce Cold Drink Cups
(g per 10,000 cold drink cups)

	PLA (2005)	HIPS	PP	PET
Waterborne Wastes				
COD	934	87.3	54.7	236
BOD	164	7.68	3.63	323
Pb+compounds as Pb	0.023	0.13	0.12	0.17
Fe+compounds as Fe	8.68	2.88	3.64	3.02
Na+compounds as Na	533	195	221	212
acid as H+	0.37	0.98	0.41	1.10
NO3-	182	0.98	12.9	0.62
Hg+compounds as Hg	3.7E-05	0.13	0.11	0.16
ammonium compounds as NH4+	0.14	1.25	0.32	0.48
Cl-	1,732	633	768	648
CN-	7.8E-05	0.13	0.11	0.16
F-	0.61	0.13	0.11	0.16
S+sulphides as S	0.0018	0.13	0.11	0.16
dissolved organics (non-hydrocarbon)	0.20	1.23	1.26	2.87
suspended solids	630	115	91.4	145
detergent/oil	1.56	3.78	2.42	4.28
hydrocarbons not specified elsewhere	0.24	1.89	0.54	17.7
organo-chlorine not specified elsewhere	3.0E-04	0.13	0.11	0.16
dissolved chlorine	2.7E-04	0.13	0.11	0.16
phenols	0.022	0.13	0.22	0.17
dissolved solids not specified elsewhere	1,860	776	948	808
P+compounds as P	1.81	0.50	10.3	0.16
other nitrogen as N	13.8	1.23	0.84	1.42
other organics not specified elsewhere	0.16	0.17	0.16	48.4
SO4--	31.4	54.1	105	62.8
dichloroethane (DCE)	0	0.13	0.11	0.16
vinyl chloride monomer (VCM)	1.5E-05	0.13	0.11	0.16
K+compounds as K	0.18	0.13	0.11	0.16
Ca+compounds as Ca	150	53.3	66.2	53.5
Mg+compounds as Mg	25.8	10.2	13.0	10.6
Cr+compounds as Cr	0.095	0.16	0.16	0.20

Greenhouse Gas Emissions

- The PP cup produces the lowest amount of CO_2 equivalents. This is due to the fact that much of the fossil fuel used in the PP drink cup is from feedstock energy, which is bound within the product and therefore does not produce greenhouse gases.
- The PLA 2005 drink cup produces a greater amount of CO_2 equivalents than the PP drink cup.
- There is no significant difference in the amount of carbon dioxide equivalents between the PLA 2005 cup system and the HIPS cup system.
- The PLA 2005 cup system creates significantly less carbon dioxide equivalents than the PET cup system.

Table 2-6 (Cont'd)

Waterborne Emissions of 16-ounce Cold Drink Cups
(g per 10,000 cold drink cups)

	PLA (2005)	HIPS	PP	PET
Waterborne Wastes				
ClO3--	0.0096	0.13	0.11	0.16
BrO3--	4.5E-05	0.13	0.11	0.16
TOC	237	4.80	0.99	6.65
AOX	3.0E-05	0.13	0.11	0.16
Al+compounds as Al	3.31	1.50	1.88	1.59
Zn+compounds as Zn	0.077	0.16	0.15	0.19
Cu+compounds as Cu	0.012	0.26	0.11	0.17
Ni+compounds as Ni	0.011	0.26	0.11	0.17
CO3--	1.19	13.5	3.81	14.3
As+compounds as As	0.011	0.13	0.11	0.17
Cd+compounds as Cd	0.0017	0.13	0.11	0.16
Mn+compounds as Mn	0.081	0.14	0.13	0.18
organo-tin as Sn	0	0.13	0.11	0.16
Ag+compounds as Ag	0.086	0.034	0.043	0.035
Ba+compounds Ba	45.1	18.9	24.3	19.6
Sr+compounds as Sr	2.23	1.00	1.23	1.07
V+compounds as V	0.0011	4.3E-04	5.6E-04	4.5E-04
organo-silicon	0	0.13	0.11	0.16
benzene	0.068	0.15	0.14	0.19
dioxin/furan as Teq	7.8E-06	0.13	0.11	0.16
Mo+compounds as Mo	9.5E-04	0.13	4.7E-04	3.8E-04
Ca++	37.4	0	0	0
PO4(-3)	0.037	0	0	0
Chromium +III	0.0012	0	0	0
Chromium +IV	7.5E-05	0	0	0
Heavy metals unspecified	5.73	0.89	1.15	0.92
Selenium	9.8E-04	1.9E-04	2.5E-04	2.0E-04
Titanium	0.031	0.013	0.017	0.014
Chlorine dissolved	7.5E-04	0	0	0
Fluorine	1.8E-04	0	0	0
Neutral salts	0.0038	0	0	0
halogenated organics	0.012	4.6E-05	5.9E-05	4.7E-05

Source: Franklin Associates, a Division of ERG

CHAPTER 3

ENERGY AND ENVIRONMENTAL RESULTS FOR 10,000 16-OUNCE 2-PIECE DELI CONTAINERS

INTRODUCTION

This chapter deals with 16-ounce two-piece deli containers. Three plastic resins used in the marketplace currently for these deli containers were modeled: PLA (polylactide), GPPS (general-purpose polystyrene), and PET (polyethylene terephthalate).

In order to express the results on an equivalent basis, a functional unit of equivalent consumer use was chosen for the deli containers in this analysis. The basis for this analysis is 10,000 16-ounce two-piece deli containers. Two companies provided samples, which were weighed by Franklin Associates staff. One company provided lightweight deli containers of both PLA and GPPS, while the other provided heavier-weight deli containers of both PLA and PET. The deli container weights include both the container and flat lid. The weights of all 16-ounce two-piece deli containers are displayed in Table 1-1 of the Introduction. Figures 3-1 through 3-3 display flow diagrams of the production of the three resins analyzed in this analysis. Figure 3-4 shows the overall life cycle of the deli containers analyzed in this report.

No secondary packaging is considered in this analysis; only the primary product is analyzed. Transportation and use of the deli containers by consumers are assumed to be equivalent for all resin systems and are not included in this study. Environmental burdens associated with end-of-life management of the deli containers are not part of the scope of this analysis. Only landfilling and combustion of the deli containers are analyzed for end-of-life management. Other end-of-life scenarios are possible, but the goal of this analysis is to analyze each material used to produce the deli containers.

ASSUMPTIONS AND LIMITATIONS

Key assumptions of the LCI of 16-ounce two-piece deli containers are as follows:

- All weight data for the lightweight deli containers (PLA and GPPS) were collected from one producer. The same is true for the heavier-weight deli containers (PLA and PET). Franklin Associates staff weighed the samples provided. Deli container weights will vary by producer and use.
- The following distances and modes were used for each resin type:
  - PLA—230 ton-miles by combination truck
  - GPPS—50 ton-miles by combination truck, 50 ton-miles by rail
  - PET—150 ton-miles by combination truck, 150 ton-miles by rail
- The disposal of the products includes landfilling of post consumer products, as well as a 20 percent waste-to-energy combustion energy credit for the incineration of post consumer products in mixed municipal

solid waste. Although it is true that most of the petroleum-based plastic can be recycled and PLA is available for composting, only a very small percentage of deli containers will actually get into the recycling and composting streams.

- The higher heating values used for the resins analyzed in this chapter are PLA—19 MJ/kg, PET—26 MJ/kg, and GPPS—40.3 MJ/kg.

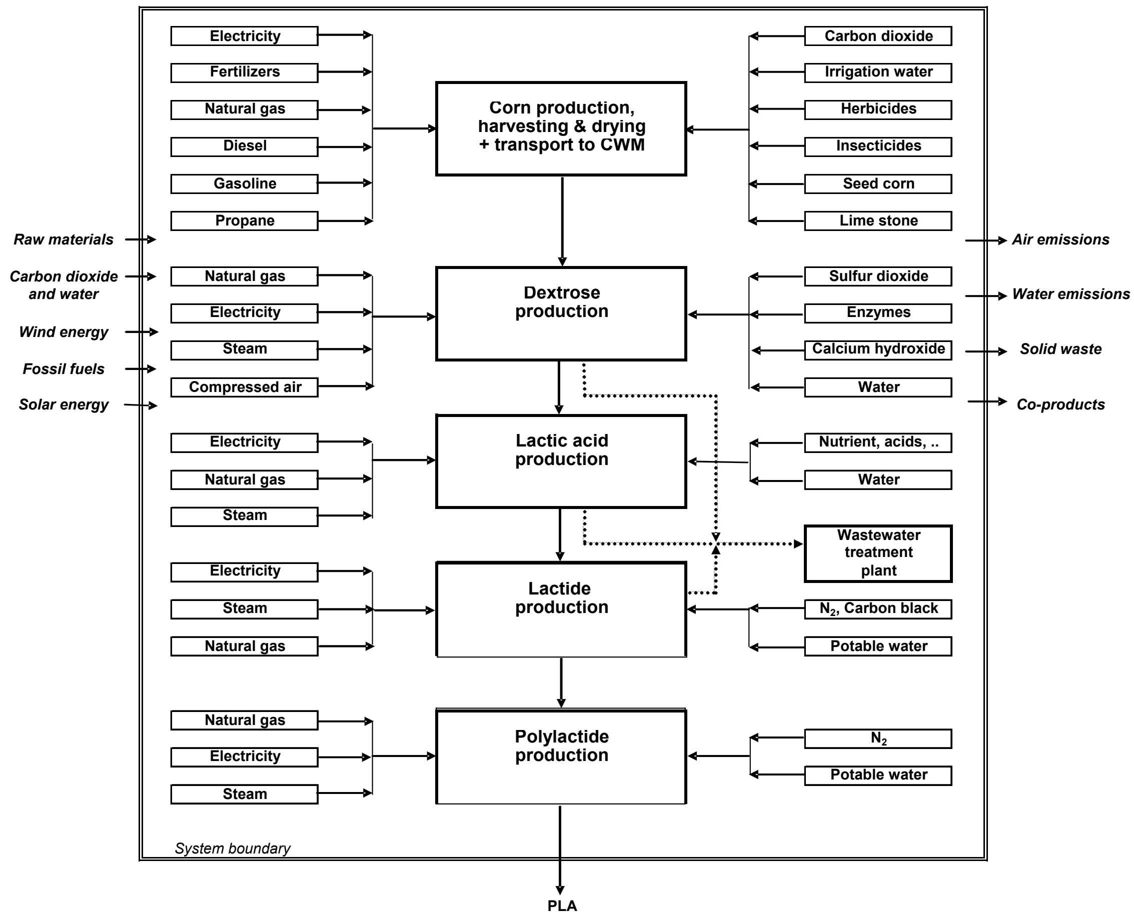

Figure 3-1. Simplified flow diagram and system boundary for the NatureWorks PLA resin production system. This flow diagram was taken from the 2006 draft journal paper provided by Dr. Erwin Vink of NatureWorks, LLC.

RESULTS

If the energy or post consumer solid waste of one system is 10 percent different from another, it can be concluded that the difference is significant. If the weight of industrial solid waste, atmospheric emissions or waterborne emissions of a system is 25 percent different from another, it can be concluded that the difference is significant. Percent difference is defined as the difference between two values divided by the average of the two values. (See Appendix D for an explanation of this certainty range.)

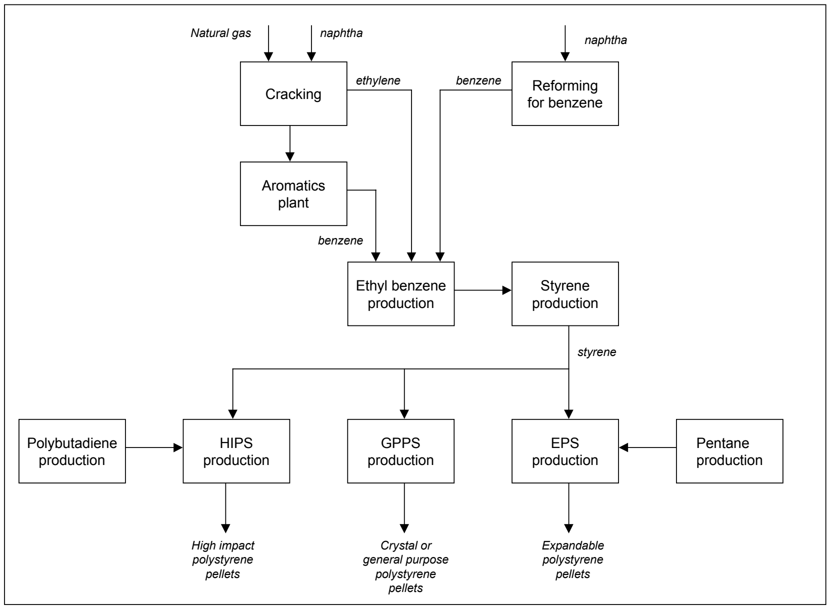

Figure 3-2. Flow diagram for the production of polystyrene resins. This flow diagram was taken from the report, **Eco-profiles of the European Plastics Industry: Polystyrene (High-Impact) (HIPS)**, PlasticsEurope, updated June, 2005.

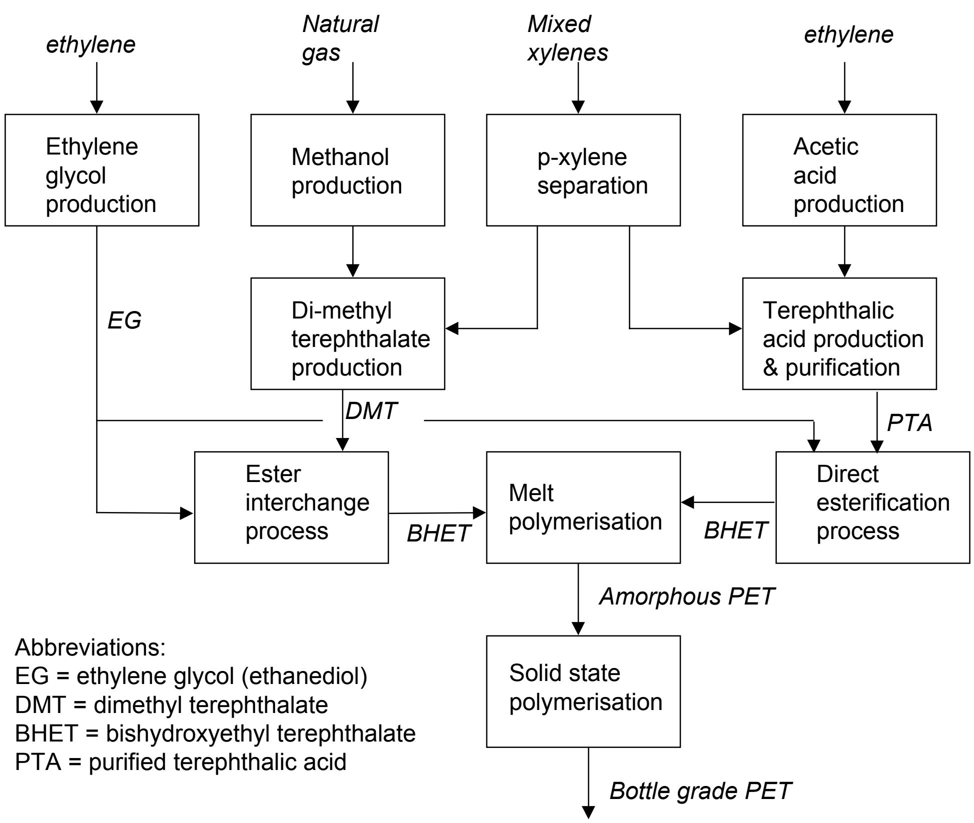

Figure 3-3. Flow diagram showing the two routes to polyethylene terephthalate (PET) resin. This flow diagram was taken from the report, **Eco-profiles of the European Plastics Industry: Polyethylene Terephthalate (PET) (Bottle grade)**, PlasticsEurope, updated March, 2005.

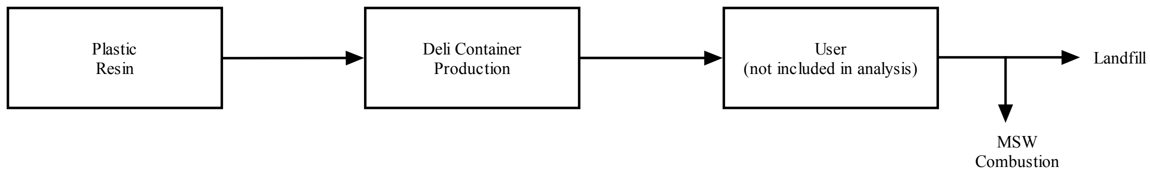

Figure 3-4. Flow diagram of the life cycle of clear 16-ounce 2-piece deli containers. Transportation to user and use phase are not included in this analysis.

Energy Results

The energy results separated into cradle-to-material and fabrication-to-grave categories are shown in Tables 3-1 and 3-2. Cradle-to-grave total energy for each deli container in Table 3-1 is separated into fuel production and delivery, energy content of delivered fuel, fuel use in transport, and feedstock energy. Table 3-1 also has a column that shows an energy credit for the energy recovered from waste-to-energy incineration of 20 percent of the post consumer solid waste. Table 3-2 breaks the total energy into fossil and non-fossil fuel.

The categories used for the breakdown of the total energy are used in the PlasticsEurope database. The following definitions are quotes from the Methodology report for the PlasticsEurope database. "*Energy content of delivered fuel* represents the energy that is received by the final operator who consumes energy. *Feedstock energy* represents the energy of the fuel bearing materials that are taken into the system but used as materials rather than fuels. *Transport energy* refers to the energy associated with fuels consumed directly by the transport operations as well as any energy associated with the production of non- fuel bearing materials, such as steel, that are taken into the transport process. *Fuel production and delivery energy* represents the energy that is used by the fuel producing industries in extracting the primary fuel from the earth, processing it and delivering it to the ultimate consumer." More information on these categories can be found in the Methodology report at PlasticsEurope's website: http://www.lca.plasticseurope.org/methodol.htm.

The PLA material (from cradle-to-resin) requires 81 percent of the total energy needed to make the lightweight 16-ounce two-piece deli containers, whereas the resin transportation, drying, thermoforming, and disposal require 19 percent of the total energy. These percentages are approximately the same for the PLA heavyweight deli container. The energy content of delivered fuel category requires the greatest amount of energy for the PLA deli containers. It makes up 41 percent of the PLA deli container's total energy requirements. Although the feedstock energy category makes up 27 percent of the total energy, much of this feedstock energy represents the corn used as raw material. It is true that corn is used as a fuel (ethanol), but less than 7 percent of the corn grown in the U.S. in 2001 was used for fuel. The fuel use in transport energy makes up 3 percent of the PLA total energy.

Table 3-1

Energy by Category for 16-ounce 2-piece Deli Containers
(MJ per 10,000 16-ounce 2-piece deli containers)

	Energy Category						
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit	Net Energy
Light-weight for handpacking							
PLA (2005)							
Cradle-to-material	3,364	5,559	327	4,596	13,845		
Fabrication-to-Grave	1,657	1,532	149	0	3,338		
Total	5,020	7,091	476	4,596	17,183	684	16,499
GPPS							
Cradle-to-material	843	5,046	210	7,038	13,137		
Fabrication-to-Grave	1,364	1,068	152	0	2,584		
Total	2,208	6,114	362	7,038	15,722	1,246	14,476
Heavy-weight for automation							
PLA (2005)							
Cradle-to-material	3,737	6,177	363	5,106	15,384		
Fabrication-to-Grave	1,865	1,702	321	0	3,888		
Total	5,602	7,879	684	5,106	19,272	760	18,512
PET							
Cradle-to-material	3,551	7,523	138	10,382	21,595		
Fabrication-to-Grave	2,361	1,835	371	0	4,567		
Total	5,912	9,358	509	10,382	26,162	1,380	24,782

	Energy Category (percent)					
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit
Light-weight for handpacking						
PLA (2005)						
Cradle-to-material	20%	32%	2%	27%	81%	
Fabrication-to-Grave	10%	9%	1%	0%	19%	
Total	29%	41%	3%	27%	100%	4%
GPPS						
Cradle-to-material	5%	32%	1%	45%	84%	
Fabrication-to-Grave	9%	7%	1%	0%	16%	
Total	14%	39%	2%	45%	100%	8%
Heavy-weight for automation						
PLA (2005)						
Cradle-to-material	19%	32%	2%	26%	80%	
Fabrication-to-Grave	10%	9%	2%	0%	20%	
Total	29%	41%	4%	26%	100%	4%
PET						
Cradle-to-material	14%	29%	1%	40%	83%	
Fabrication-to-Grave	9%	7%	1%	0%	17%	
Total	23%	36%	2%	40%	100%	5%

Source: Franklin Associates, a Division of ERG

Using the percent difference calculation as described above, the following conclusions can be made about a comparison of the total energy requirements of 16-ounce two-piece deli containers. Comparing the lightweight deli containers, the PLA 2005 deli containers require the most total energy; however, the GPPS deli container energy is not considered significantly different from the PLA 2005 deli container. Comparing the heavyweight deli containers, the PET deli container requires significantly more energy than the PLA deli containers. This correlates with the fact that the PET deli container is heavier than the PLA deli container in this case.

Also included in Table 3-1 is the energy recovered from the combustion of 20 percent of post consumer deli containers that are discarded, based on the national average percentage of municipal solid waste that is disposed by waste-to-energy combustion[2]. These are calculated using the higher heating value of the resin used multiplied by 20 percent of the weight of the deli containers disposed. The higher heating value (HHV) of PLA is less than the petroleum-based resins; therefore, less combustion energy credit is given to the PLA deli containers. The HHV for each resin is found in the Assumptions and Limitations section of this chapter. If combustion energy credit is given, the net energy conclusions do differ from the total energy conclusions regarding the lightweight PLA deli container. The lightweight PLA 2005 deli container is significantly higher than the GPPS deli container. The conclusions for the heavyweight deli containers do not change from the energy requirements without giving combustion credit.

Table 3-2 shows the fuel sources of cradle-to-production energy by fossil and non-fossil fuel for 10,000 16-ounce two-piece deli containers. All four categories shown in Table 3-1 are included in the total energy results shown in the table. The fossil fuels include natural gas, petroleum and coal. These fuels are commonly used for direct combustion for process fuels and generation of electricity. Natural gas and petroleum are also used as raw material inputs for the production of petroleum-based plastics. Petroleum is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear, biomass, wind, and other (geothermal, etc.) shown in the table are used to generate electricity along with the fossil fuels. It should be noted that corn as feedstock energy is considered biomass and therefore in the non-fossil fuel.

The PLA deli containers require 64 percent fossil fuel use, with the remainder coming from non-fossil sources. This is due to the feedstock energy, which is from corn, a non-fossil source. The petroleum-based plastic deli containers require greater than 90 percent fossil fuel use. The feedstock energy of the petroleum-based plastic deli containers makes up between 44 and 48 percent of the fossil fuel required for those deli containers.

2 Municipal Solid Waste in the United States: 2001 Facts and Figures. U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. August 2003.

Table 3-2

Energy by Fuel Type for 16-ounce 2-piece Deli Containers
(MJ per 10,000 16-ounce 2-piece deli containers)

	Fuel Type			Fuel Type (percent)		
	Fossil Fuel	Non-fossil Fuel	Total	Fossil Fuel	Non-fossil Fuel	Total
Light-weight for handpacking						
PLA (2005)						
Cradle-to-material	8,396	5,449	13,845	49%	32%	81%
Fabrication-to-Grave	2,613	725	3,338	15%	4%	19%
Total	11,009	6,174	17,183	64%	36%	100%
GPPS						
Cradle-to-material	12,731	406	13,137	81%	3%	84%
Fabrication-to-Grave	2,025	560	2,585	13%	4%	16%
Total	14,756	966	15,722	94%	6%	100%
Heavy-weight for automation						
PLA (2005)						
Cradle-to-material	9,329	6,055	15,384	48%	31%	80%
Fabrication-to-Grave	3,081	807	3,888	16%	4%	20%
Total	12,410	6,862	19,272	64%	36%	100%
PET						
Cradle-to-material	20,182	1,413	21,595	77%	5%	83%
Fabrication-to-Grave	3,604	963	4,568	14%	4%	17%
Total	23,786	2,376	26,162	91%	9%	100%

Source: Franklin Associates, a Division of ERG

Solid Waste

Solid waste details separated into cradle-to-material and fabrication-to-grave categories are shown in Tables 3-3a and 3-3b. Solid waste is categorized into empirical categories, following the methodology of the PlasticsEurope database. According to the PlasticsEurope methodology report, "in the empirical system, the aim is to categorize solid waste into the smallest number of different categories that identify the type of disposal that has to be applied or the use, if any, to which the waste can be put after appropriate processing". Also included in the solid waste table are post consumer wastes, which are the wastes discarded by the end users of the product.

No solid waste data were provided in Dr. Vink's journal paper for the PLA 2005 resin. The solid waste data shown for the PLA resin in Tables 3-3a and 3-3b are estimated from the PLA (2006) dataset and do not include the solid waste credited for the purchase of wind energy credits. In many of the categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.

Table 3-3a

Solid Wastes for 16-ounce 2-piece Deli Containers
(Light-Weight for Handpacking)
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)			GPPS		
	Cradle-to-PLA resin	Fab-to-Grave	Total (1)	Cradle-to-GPPS resin	Fab-to-Grave	Total
Solid Waste Categories						
Plastic containers	0	0	0	0.15	0	0.15
Paper	0	5,367	5,367	3.34	4,443	4,446
Plastics	184	101	285	10.6	83.6	94.3
Metals	0	2.52	2.52	14.4	2.08	16.5
Putrescibles	0	0	0	0.46	0	0.46
Unspecified refuse	193	732	925	289	606	895
Mineral waste	3,382	626	4,009	289	518	807
Slags & ash	83.4	3,217	3,300	1,520	1,031	2,551
Mixed industrial	414	83.8	498	274	69.3	343
Regulated chemicals	812	90,771	91,583	623	75,139	75,762
Unregulated chemicals	209	498	707	441	413	853
Construction waste	0.37	0	0.37	11.6	0	11.6
Waste to incinerator	0	272	272	3,800	225	4,025
Inert chemical	0.18	145	145	410	120	530
Wood waste	0	50.7	50.7	0.15	41.9	42.1
Wooden pallets	0	2.73	2.73	0.30	2.26	2.56
Waste to recycling	0.18	32.5	32.7	48.6	26.9	75.6
Waste returned to mine	2.39	1,995	1,997	6,839	1,651	8,490
Tailings	1,786	0	1,786	1,155	0	1,155
Municipal solid waste	0	1,200	1,200	-3.2E+02	994	675
Postconsumer solid waste	0	144,000	144,000	0	119,200	119,200

(1) No solid waste data were provided in Dr. Vink's journal paper for the PLA(2005) resin. The data shown for the resin is estimated from the PLA(2006) dataset and does not include the solid waste credited for the purchase of wind energy credits.

Source: Franklin Associates, a Division of ERG

Post consumer wastes are the wastes discarded by the final users of the product. As we are including the U.S. average combustion of mixed municipal solid waste, 20 percent of that weight is combusted in waste-to-energy facilities and therefore subtracted out of the total post consumer wastes. The weight of post consumer wastes is directly related to the weight of a product. Therefore, heavier products produce more post consumer solid wastes. For the light-weight 16-ounce two-piece deli container, the PLA deli container is the heaviest and so produces the most post consumer solid waste. For the heavy-weight 16-ounce two-piece deli container, the PET deli container is the heaviest and so produces the most post consumer solid waste.

Table 3-3b

Solid Wastes for 16-ounce 2-piece Deli Containers
(Heavy-Weight for Automation)
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)			PET		
	Cradle-to-PLA resin	Fab-to-Grave	Total (1)	Cradle-to-PET resin	Fab-to-Grave	Total
Solid Waste Categories						
Plastic containers	0	0	0	0.26	0	0.26
Paper	0	5,963	5,963	0.26	7,633	7,633
Plastics	204	112	316	601	144	744
Metals	0	2.80	2.80	0.26	3.58	3.84
Putrescibles	0	0	0	0.26	0	0.26
Unspecified refuse	214	814	1,028	392	1,042	1,433
Mineral waste	3,758	696	4,454	104	891	995
Slags & ash	92.6	3,761	3,853	5,745	1,902	7,647
Mixed industrial	460	93.1	553	366	119	485
Regulated chemicals	902	100,857	101,759	731	129,097	129,828
Unregulated chemicals	232	554	786	2,324	709	3,033
Construction waste	0.41	0	0.41	14.1	0	14.1
Waste to incinerator	0	302	302	209	387	596
Inert chemical	0.20	161	161	496	206	703
Wood waste	0	56.3	56.3	0.26	72.0	72.3
Wooden pallets	0	3.03	3.03	0.26	3.88	4.14
Waste to recycling	0.20	36.2	36.4	47.0	46.3	93.3
Waste returned to mine	2.65	2,216	2,219	14,884	2,837	17,721
Tailings	1,984	0	1,984	0.78	0	0.78
Municipal solid waste	0	1,334	1,334	1,802	1,707	3,509
Postconsumer solid waste	0	160,000	160,000	0	204,800	204,800

(1) No solid waste data were provided in Dr. Vink's journal paper for the PLA(2005) resin. The data shown for the resin is estimated from the PLA(2006) dataset and does not include the solid waste credited for the purchase of wind energy credits.

Source: Franklin Associates, a Division of ERG

Environmental Emissions

Atmospheric and waterborne emissions for each system include emissions from processes and those associated with the combustion of fuels. Tables 3-4a and 3-4b present atmospheric emissions results and Tables 3-6a and 3-6b show waterborne emissions for 10,000 16-ounce two-piece deli containers. Table 3-5 gives a greenhouse gas summary for each of the deli container systems analyzed. Atmospheric and waterborne emissions from the Franklin Associates fuel emissions model were limited to the emissions used in the PlasticsEurope database for consistency in reporting. A common practice in the PlasticsEurope database is the use of "<1" for emissions with less than 1 mg of emission per kg of product. In this analysis, the value "1" represents all "<1" values given by PlasticsEurope. This is the upper limit of these values, and so the values may be overstated by an unknown amount.

There are significant uncertainties with regard to the application of the data to the deli container systems. Because of these uncertainties, two systems' emissions of a given

substance are not considered significantly different unless the percent difference exceeds 25 percent. (Percent difference is defined as the difference between two system totals divided by their average.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix D).

It is important to realize that interpretation of air and water emission data requires great care. The effects of the various emissions on humans and on the environment are not fully known. The degree of potential environmental disruption due to environmental releases is not related to the weight of the releases in a simple way. No firm conclusions can be made from the various atmospheric or waterborne emissions that result from the product systems. Only comprehensive tables of the atmospheric and waterborne emissions are shown here.

Atmospheric Emissions. The predominant atmospheric emissions from the product systems include greenhouse gases (particularly carbon dioxide, methane, and nitrous oxide), nitrogen oxides, sulfur oxides, particulates (PM10), and hydrocarbons. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different air emissions or groups of air emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, *methane*, *aromatic hydrocarbons* and *polycyclic hydrocarbons* have been identified as separate groups with the more general heading of *hydrocarbons* being reserved for the remainder. When such a split has been introduced, there is no double counting. For example, if a benzene emission is included in the *aromatics* group, it is not included in the more general category of *hydrocarbons*."

Tables 3-4a and 3-4b display the individual atmospheric emissions for each of the deli container systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various atmospheric emissions that result from the deli container systems.

Greenhouse Gases. This analysis is not an LCIA (life cycle impact assessment) and thus the impacts of various environmental emissions are not evaluated. However, due to our understanding of the relationship between greenhouse gases and global warming, it is reasonable to develop conclusions based on the quantity of greenhouse gases generated by a system. Greenhouse gas emissions are expressed as carbon dioxide equivalents, which use global warming potentials developed by the International Panel on Climate Change (IPCC) to normalize the various greenhouse gases to an equivalent weight of carbon dioxide. The 100-year time horizon Global Warming Potentials for GHG was used for this analysis.

Greenhouse gas emissions are closely related to system fossil energy, and thus the trends observed for system fossil energy requirements also apply to system greenhouse

gas emissions. The carbon dioxide equivalents for the lightweight PLA 2005 deli container are not significantly different from those of the GPPS deli container. This is due to the fact that much of the fossil fuel used in the GPPS deli container is from feedstock energy, which is bound within the product and therefore does not produce greenhouse gases, as well as the lower weight of the GPPS deli container. The carbon dioxide equivalents for the heavyweight PET deli container system are significantly greater than the carbon dioxide equivalents for the heavyweight PLA deli container system.

Waterborne Emissions. The predominant waterborne emissions from the container systems include dissolved solids, suspended solids, COD (chemical oxygen demand), BOD (biological oxygen demand), chlorides, and various metals. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different water emissions or groups of water emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, some specific metal ions are identified separately from the more general heading of metals. When such a split has been introduced, there is no double counting. For example, if a Na+ emission is identified, it is not included in the more general category of *metals (unspecified).* However, some operators may not necessarily have reported separately all of the metals specifically identified elsewhere in the table. As a consequence, the category *metals (unspecified)* may well include some metals that were specifically identified by other companies and are included under the appropriate specific heading elsewhere in the table."

Tables 3-6a and 3-6b display the individual waterborne emissions for each of the deli container systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various waterborne emissions that result from the deli container systems.

CONCLUSIONS

A life cycle inventory (LCI) is an environmental profile that expresses environmental burdens from the perspective of energy consumption, solid waste generation, atmospheric emissions, and waterborne emissions. This LCI evaluated lightweight and heavyweight 16-ounce two-piece deli container systems and found that three types of environmental burdens were helpful in distinguishing the LCI results: 1) energy requirements, 2) solid waste generation, and 3) greenhouse gas emissions. The LCI conclusions for each of these categories are summarized below.

Table 3-4a

Atmospheric Emissions of 16-ounce 2-piece Deli Containers
(Light-Weight for Handpacking)
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)	GPPS
Atmospheric Emissions		
dust (PM10)	1,825	198
CO	1,586	1,073
CO2	466,010	548,897
SOX as SO2	3,083	2,286
H2S	0.37	0.30
mercaptan	3.7E-04	0.15
NOX as NO2	3,286	1,355
NH3	0.98	0.22
Cl2	0.029	0.15
HCl	78.7	13.8
F2	1.8E-05	0.15
HF	3.34	0.61
hydrocarbons not specified elsewhere	585	642
aldehyde (-CHO)	0.15	0.29
organics	14.8	35.8
Pb+compounds as Pb	0.0016	0.15
Hg+compounds as Hg	3.2E-04	0.15
metals not specified elsewhere	0.85	1.05
H2SO4	0.0025	0.15
N2O	67.8	0.52
H2	31.4	12.2
dichloroethane (DCE) C2H4Cl2	3.7E-05	0.15
vinyl chloride monomer (VCM)	6.1E-04	0.15
CFC/HCFC/HFC not specified elsewhere	4.1E-07	0.15
organo-chlorine not specified elsewhere	1.84	0.15
HCN	0	0.15
CH4	4,473	5,822
aromatic HC not specified elsewhere	0.81	5.22
polycyclic hydrocarbons (PAH)	6.3E-05	0.46
NMVOC	80.7	29.5
CS2	0	0.15
methylene chloride CH2Cl2	0.0012	0.15
Cu+compounds as Cu	7.9E-05	0.15
As+compounds as As	0.0015	0.15
Cd+compounds as Cd	2.3E-04	0.15
Ag+compounds as Ag	0	0.15
Zn+compounds as Zn	4.1E-04	0.15
Cr+compounds as Cr	0.0010	0.30
Se+compounds as Se	0.0042	0.15
Ni+compounds as Ni	0.0046	0.46
Sb+compounds as Sb	1.1E-04	0.15

Table 3-4a (Cont'd)

Atmospheric Emissions of 16-ounce 2-piece Deli Containers
(g per 10,000 16-ounce 2-piece deli containers)

Atmospheric Emissions	PLA (2005)	GPPS
ethylene oxide C2H4O	0	0
ethylene C2H4	0	1.06
oxygen	0	0.15
asbestos	0	0.15
dioxin/furan as Teq	1.6E-07	0.15
benzene C6H6	0.12	3.52
toluene C7H8	0.17	0.63
xylenes C8H10	0.099	0.17
ethylbenzene C8H10	0.012	6.08
HCFC-22 CHClF2	0.18	0.30
styrene	3.7E-08	11.4
propylene	0.034	0.79
Fe+compounds as Fe	4.2E-04	0
Co+compounds as Co	5.7E-04	8.2E-05
V+compounds as V	0.0022	0
Al+compounds as Al	-0.76	0
B+compounds as B	9.4E-04	0
Manganese	0.0019	1.6E-04
Molybdenum	1.8E-05	0
Corn dust	13.8	0
Tin	9.2E-05	0
Titanium	1.8E-05	0
Barium	0.065	0
Beryllium	6.9E-05	2.5E-06
Bromine	7.7E-04	0
Cyanide (unspecified)	1.7E-04	1.1E-07
Fluoride (unspecified)	3.0E-04	7.8E-06
Helium	0.070	0
VOC (volatile organic compou	0.045	0
Dust (PM 2.5)	2.74	0
Dust (unspecified)	23.2	1.09
Ethanol	83.6	0
Lactic acid	0.16	0
Particles (< 2.5 um)	-3.84	0
Particles (> 10 um)	-46.9	0
Particles (<10 and > 2.5 um)	-42.0	0

Source: Franklin Associates, a Division of ERG

Table 3-4b

Atmospheric Emissions of 16-ounce 2-piece Deli Containers
(Heavy-Weight for Automation)
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)	PET
Atmospheric Emissions		
dust (PM10)	2,030	603
CO	1,832	2,364
CO2	531,160	1,004,693
SOX as SO2	3,432	4,638
H2S	0.41	0.51
mercaptan	4.2E-04	0.26
NOX as NO2	3,742	2,918
NH3	1.16	0.44
Cl2	0.032	0.26
HCl	87.5	52.2
F2	2.0E-05	0.26
HF	3.72	2.10
hydrocarbons not specified elsewhere	658	2,544
aldehyde (-CHO)	0.32	0.61
organics	16.4	82.4
Pb+compounds as Pb	0.0019	0.26
Hg+compounds as Hg	3.6E-04	0.26
metals not specified elsewhere	0.95	1.80
H2SO4	0.0028	0.26
N2O	75.6	1.11
H2	34.9	43.9
dichloroethane (DCE) C2H4Cl2	4.1E-05	0.26
vinyl chloride monomer (VCM)	6.7E-04	0.26
CFC/HCFC/HFC not specified elsewhere	8.8E-07	0.26
organo-chlorine not specified elsewhere	2.04	0.26
HCN	0	0.26
CH4	4,987	7,142
aromatic HC not specified elsewhere	0.90	94.9
polycyclic hydrocarbons (PAH)	7.2E-05	1.83
NMVOC	94.0	356
CS2	0	0.26
methylene chloride CH2Cl2	0.0014	0.26
Cu+compounds as Cu	8.9E-05	0.26
As+compounds as As	0.0017	0.26
Cd+compounds as Cd	2.7E-04	0.26
Ag+compounds as Ag	0	0.26
Zn+compounds as Zn	4.5E-04	0.26
Cr+compounds as Cr	0.0011	1.04
Se+compounds as Se	0.0048	0.26
Ni+compounds as Ni	0.0063	1.83
Sb+compounds as Sb	1.3E-04	0.26

Table 3-4b (Cont'd)

Atmospheric Emissions of 16-ounce 2-piece Deli Containers
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)	PET
Atmospheric Emissions		
ethylene oxide C2H4O	0	0.26
ethylene C2H4	0	0.52
oxygen	0	0.26
asbestos	0	0.26
dioxin/furan as Teq	2.7E-07	0.26
benzene C6H6	0.15	0.58
toluene C7H8	0.21	0.32
xylenes C8H10	0.12	0.30
ethylbenzene C8H10	0.016	0.27
HCFC-22 CHClF2	0.20	0.25
styrene	4.2E-08	0.26
propylene	0.038	0.31
Fe+compounds as Fe	4.7E-04	0
Co+compounds as Co	7.2E-04	2.0E-04
V+compounds as V	0.0025	0
Al+compounds as Al	-0.84	0
B+compounds as B	0.0010	0
Manganese	0.0023	4.0E-04
Molybdenum	2.0E-05	0
Corn dust	15.3	0
Tin	1.0E-04	0
Titanium	2.0E-05	0
Barium	0.072	0
Beryllium	7.9E-05	6.3E-06
Bromine	8.6E-04	0
Cyanide (unspecified)	1.9E-04	2.8E-07
Fluoride (unspecified)	3.4E-04	1.9E-05
Helium	0.078	0
VOC (volatile organic compou	0.050	0
Dust (PM 2.5)	3.05	0
Dust (unspecified)	26.9	2.72
Ethanol	92.9	0
Lactic acid	0.18	0
Particles (< 2.5 um)	-4.27	0
Particles (> 10 um)	-52.1	0
Particles (<10 and > 2.5 um)	-46.7	0

Source: Franklin Associates, a Division of ERG

Table 3-5

Greenhouse Gas Summary for 16-ounce 2-piece Deli Containers
(g of carbon dioxide equivalents per 10,000 16-ounce 2-piece deli containers)

	Light-weight for handpacking		Heavy-weight for automation	
	PLA (2005)	GPPS	PLA (2005)	PET
CO2	466,010	548,897	531,160	1,004,693
N2O	20,055	153	22,379	330
CFC/HCFC/HFC not specified elsewhere	6.9E-04	258	0.0015	444
CH4	102,877	133,902	114,700	164,274
methylene chloride CH2Cl2	0.012	1.52	0.014	2.61
HCFC-22 CHClF2	300	506	333	426
Total	589,243	683,718	668,572	1,170,169

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, nitrous oxide--296, CFC/HCFCs--1700, methane--23, methylene chloride--10, HCFC22--1700.

Source: Franklin Associates, a Division of ERG

Energy Requirements

- Comparing the lightweight deli containers, the GPPS deli container energy is not considered significantly different from the PLA 2005 deli container.
- Comparing the heavyweight deli containers, the PET deli container requires significantly more energy than the PLA deli container.
- If combustion energy credit is given, the net energy conclusions for the lightweight deli containers do differ (due to the different HHVs and weights of deli containers) from the total energy conclusions as follows:
  - The lightweight PLA 2005 deli container is significantly higher than the GPPS deli container.
  - The petroleum-based plastic deli containers require more fossil fuel than the PLA deli containers. This is due in a large part to the feedstock energy of the petroleum-based plastic deli containers.

Solid Waste Generation

- In many of the empirical solid waste categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.
- For the lightweight 16-ounce two-piece deli container, the PLA deli container is the heaviest and so produces the most post consumer solid waste.
- For the heavyweight 16-ounce two-piece deli container, the PET deli container is the heaviest and so produces the most post consumer solid waste.

Greenhouse Gas Emissions

- The carbon dioxide equivalents for the lightweight PLA 2005 deli container are not significantly different than for the GPPS deli container.
- The carbon dioxide equivalents for the heavyweight PET deli container system are significantly greater than for the heavy-weight PLA deli container system.

Table 3-6a

Waterborne Emissions of 16-ounce 2-piece Deli Containers
(Light-Weight for Handpacking)
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)	GPPS
Waterborne Wastes		
COD	1,133	97.7
BOD	199	7.78
Pb+compounds as Pb	0.0093	0.16
Fe+compounds as Fe	5.09	2.40
Na+compounds as Na	324	172
acid as H+	0.44	1.03
NO3-	222	1.19
Hg+compounds as Hg	1.4E-05	0.15
ammonium compounds as NH4+	0.17	1.98
Cl-	957	536
CN-	9.3E-05	0.15
F-	0.74	0.15
S+sulphides as S	6.6E-04	0.15
dissolved organics (non-hydrocarbon)	0.24	1.49
suspended solids	682	115
detergent/oil	1.17	4.58
hydrocarbons not specified elsewhere	0.29	2.43
organo-chlorine not specified elsewhere	3.7E-04	0.15
dissolved chlorine	3.3E-04	0.15
phenols	0.010	0.16
dissolved solids not specified elsewhere	844	656
P+compounds as P	2.20	0.46
other nitrogen as N	16.8	1.64
other organics not specified elsewhere	0.11	0.19
SO4--	35.6	66.6
dichloroethane (DCE)	0	0.15
vinyl chloride monomer (VCM)	1.8E-05	0.15
K+compounds as K	0.22	0.15
Ca+compounds as Ca	80.6	44.0
Mg+compounds as Mg	11.4	8.37
Cr+compounds as Cr	0.038	0.18
ClO3--	0.012	0.15
BrO3--	5.5E-05	0.15

Table 3-6a (Cont'd)

Waterborne Emissions of 16-ounce 2-piece Deli Containers
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)	GPPS
Waterborne Wastes		
TOC	288	6.42
AOX	3.7E-05	0.15
Al+compounds as Al	1.29	1.28
Zn+compounds as Zn	0.031	0.18
Cu+compounds as Cu	0.0051	0.31
Ni+compounds as Ni	0.0047	0.31
CO3--	1.44	19.4
As+compounds as As	0.0048	0.16
Cd+compounds as Cd	7.4E-04	0.15
Mn+compounds as Mn	0.064	0.17
organo-tin as Sn	0	0.15
SO3--	0	0.15
Ag+compounds as Ag	0.037	0.027
Ba+compounds Ba	17.3	15.4
Sr+compounds as Sr	0.98	0.87
V+compounds as V	4.8E-04	3.6E-04
organo-silicon	0	0.15
benzene	0.030	0.17
dioxin/furan as Teq	3.4E-06	0.15
Mo+compounds as Mo	4.3E-04	0.15
Ca++	45.5	0
PO4(-3)	0.045	0
Chromium +III	0.0014	0
Chromium +IV	9.2E-05	0
Heavy metals unspecified	5.20	0.73
Selenium	8.2E-04	1.6E-04
Titanium	0.012	0.011
Chlorine dissolved	9.2E-04	0
Fluorine	2.2E-04	0
Neutral salts	0.0047	0
halogenated organics	0.014	3.7E-05

Source: Franklin Associates, a Division of ERG

Table 3-6b

Waterborne Emissions of 16-ounce 2-piece Deli Containers
(Heavy-Weight for Automation)
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)	PET
Waterborne Wastes		
COD	1,260	383
BOD	221	523
Pb+compounds as Pb	0.019	0.28
Fe+compounds as Fe	8.11	5.86
Na+compounds as Na	506	400
acid as H+	0.49	1.78
NO3-	246	1.00
Hg+compounds as Hg	2.9E-05	0.26
ammonium compounds as NH4+	0.19	0.78
Cl-	1,581	1,253
CN-	1.0E-04	0.26
F-	0.83	0.26
S+sulphides as S	0.0014	0.26
dissolved organics (non-hydrocarbon)	0.27	4.64
suspended solids	796	250
detergent/oil	1.63	7.06
hydrocarbons not specified elsewhere	0.33	28.7
organo-chlorine not specified elsewhere	4.1E-04	0.26
dissolved chlorine	3.7E-04	0.26
phenols	0.019	0.28
dissolved solids not specified elsewhere	1,577	1,560
P+compounds as P	2.44	0.26
other nitrogen as N	18.6	2.30
other organics not specified elsewhere	0.16	78.4
SO4--	40.7	102
dichloroethane (DCE)	0	0.26
vinyl chloride monomer (VCM)	2.0E-05	0.26
K+compounds as K	0.25	0.26
Ca+compounds as Ca	136	105
Mg+compounds as Mg	21.7	20.7
Cr+compounds as Cr	0.077	0.34
ClO3--	0.013	0.26
BrO3--	6.1E-05	0.26

Table 3-6b (Cont'd)

Waterborne Emissions of 16-ounce 2-piece Deli Containers
(g per 10,000 16-ounce 2-piece deli containers)

	PLA (2005)	PET
Waterborne Wastes		
TOC	320	10.8
AOX	4.1E-05	0.26
Al+compounds as Al	2.67	3.06
Zn+compounds as Zn	0.062	0.33
Cu+compounds as Cu	0.0097	0.27
Ni+compounds as Ni	0.0091	0.27
CO3--	1.60	23.1
As+compounds as As	0.0093	0.27
Cd+compounds as Cd	0.0014	0.26
Mn+compounds as Mn	0.087	0.30
organo-tin as Sn	0	0.26
SO3--	0	0
Ag+compounds as Ag	0.071	0.068
Ba+compounds Ba	36.2	38.4
Sr+compounds as Sr	1.87	2.04
V+compounds as V	9.3E-04	8.8E-04
organo-silicon	0	0.26
benzene	0.057	0.32
dioxin/furan as Teq	6.5E-06	0.26
Mo+compounds as Mo	8.0E-04	7.5E-04
Ca++	50.5	0
PO4(-3)	0.050	0
Chromium +III	0.0016	0
Chromium +IV	1.0E-04	0
Heavy metals unspecified	6.57	1.81
Selenium	0.0011	3.9E-04
Titanium	0.025	0.027
Chlorine dissolved	0.0010	0
Fluorine	2.4E-04	0
Neutral salts	0.0052	0
halogenated organics	0.016	9.3E-05

Source: Franklin Associates, a Division of ERG

CHAPTER 4

ENERGY AND ENVIRONMENTAL RESULTS FOR 1,000,000 SQUARE INCHES OF ENVELOPE WINDOW FILM

INTRODUCTION

This chapter focuses on envelope window film. Two plastic resins used in the marketplace currently for envelope windows are modeled: PLA (polylactide) and GPPS (general-purpose polystyrene).

In order to express the results on an equivalent basis, a functional unit of an equivalent area and gauge was chosen for the envelope window film in this analysis. The basis for this analysis is 1,000,000 square inches of envelope window film for a standard gauge of 0.115 (1.15 mil). Weights for the envelope windows in this analysis were taken from the Alcoa Kama website for GPPS and from the Plastic Suppliers website for PLA. The weights of the envelope windows are displayed in Table 1-1 of the Introduction. Figures 4-1 and 4-2 display flow diagrams of the production of the two resins analyzed in this analysis. Figure 4-3 shows the overall life cycle of the envelope windows analyzed.

No secondary packaging is considered in this analysis; only the primary product is analyzed. Transportation, insertion into envelopes, and use of the envelope windows by consumers are assumed to be equivalent for all resin systems and are not included in this study. Environmental burdens associated with end-of-life management of the envelope windows are not part of the scope of this analysis. Only landfilling and combustion of the envelope windows are analyzed for end-of-life management. Other end-of-life scenarios are possible, but the goal of this analysis is to analyze each material used to produce the envelope windows.

ASSUMPTIONS AND LIMITATIONS

Key assumptions of the LCI of envelope window film are as follows:

- Weights for the envelope windows in this analysis were taken from the Alcoa Kama website for GPPS and from the Plastic Suppliers website for PLA. Window film weights will vary by producer.
- The following distances and modes were used for each resin type:
    - PLA—395 ton-miles by combination truck
    - GPPS—120 ton-miles by combination truck, 120 ton-miles by rail
- The disposal of the products includes landfilling of post consumer products, as well as a 20 percent waste-to-energy (WTE) combustion energy credit for the incineration of post consumer products in mixed municipal solid waste. Although it is true that most of the petroleum-based plastic can be recycled and PLA is available for composting, it is very

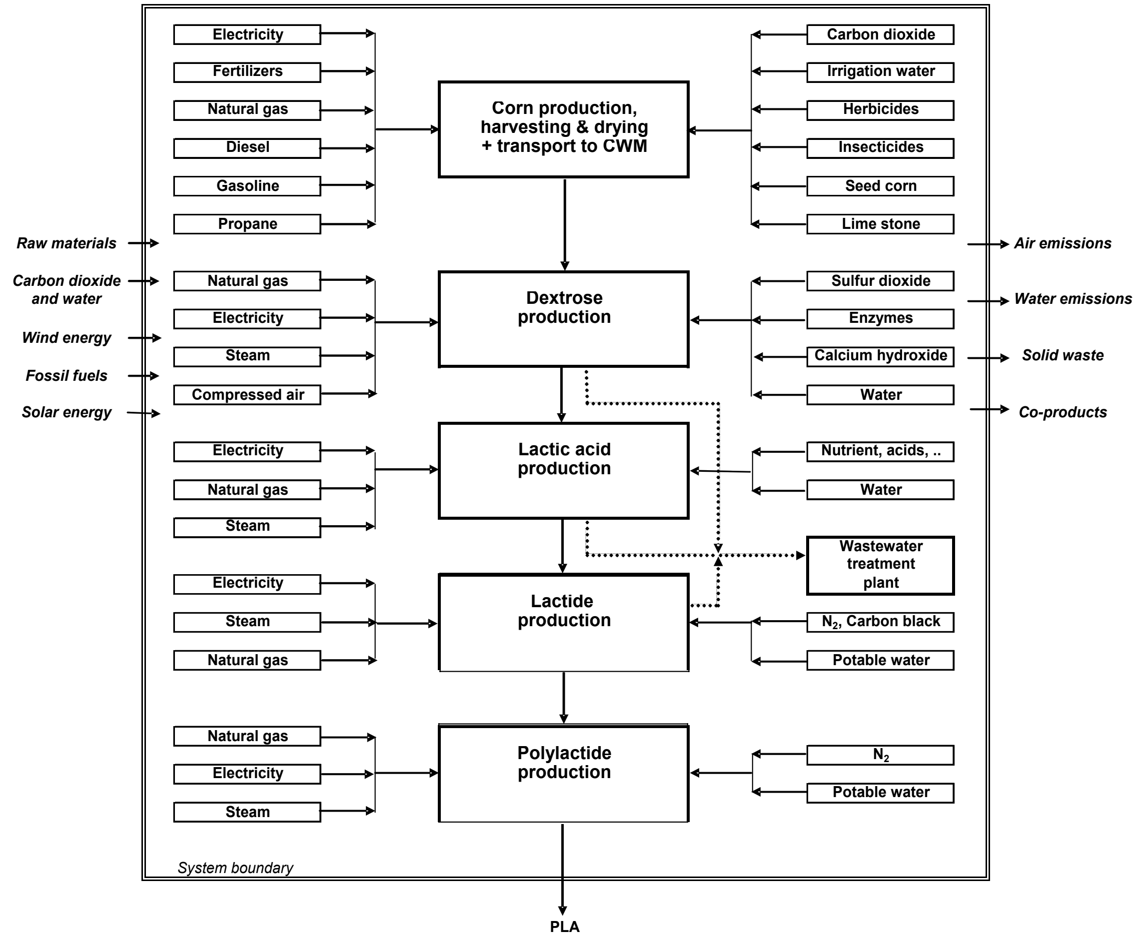

Figure 4-1. Simplified flow diagram and system boundary for the NatureWorks PLA resin production system. This flow diagram was taken from the 2006 draft journal paper provided by Dr. Erwin Vink of NatureWorks, LLC.

unlikely that the envelope windows will actually get into the recycling and composting streams.

- The higher heating values used for the resins analyzed in this chapter are PLA—19 MJ/kg and GPPS—40.3 MJ/kg.

RESULTS

If the energy or post consumer solid waste of one system is 10 percent different from another, it can be concluded that the difference is significant. If the weight of industrial solid waste, atmospheric emissions or waterborne emissions of a system is 25 percent different from another, it can be concluded that the difference is significant. Percent difference is defined as the difference between two values divided by the average of the two values. (See Appendix D for an explanation of this certainty range.)

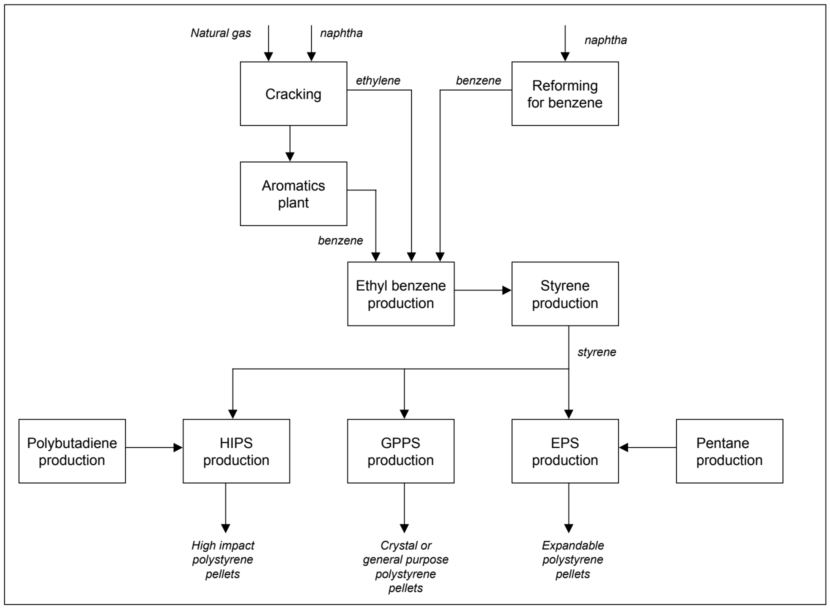

Figure 4-2. Flow diagram for the production of polystyrene resins. This flow diagram was taken from the report, **Eco-profiles of the European Plastics Industry: Polystyrene (High-Impact) (HIPS)**, PlasticsEurope, updated June, 2005.

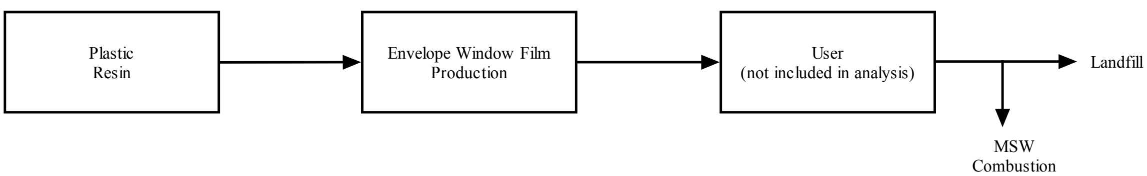

Figure 4-3. Flow diagram of the life cycle of envelope window film. Transportation to user and use phase are not included in this analysis.

Energy Results

The energy results separated into cradle-to-material and fabrication-to-grave categories for 1,000,000 square inches of envelope window film are shown in Tables 4-1 and 4-2. Cradle-to-grave total energy for envelope window film in Table 4-1 is separated into fuel production and delivery, energy content of delivered fuel, fuel use in transport, and feedstock energy. Table 4-1 also has a column that shows an energy credit for the energy recovered from waste-to-energy incineration of 20 percent of the post consumer solid waste. Table 4-2 breaks the total energy into fossil and non-fossil fuel.

The categories used for the breakdown of the total energy are used in the PlasticsEurope database. The following definitions are quotes from the Methodology report for the PlasticsEurope database. "*Energy content of delivered fuel* represents the energy that is received by the final operator who consumes energy. *Feedstock energy* represents the energy of the fuel bearing materials that are taken into the system but used as materials rather than fuels. *Transport energy* refers to the energy associated with fuels consumed directly by the transport operations as well as any energy associated with the

Table 4-1

Energy by Category for Envelope Window Film
(MJ per 1 million square inches)

	Energy Category						
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit	Net Energy
Envelope Window Film							
PLA (2005)							
Cradle-to-material	438	723	42.5	598	1,801		
Fabrication-to-Grave	102	84.0	43.0	0	229		
Total	540	807	85.5	598	2,030	89.7	1,941
GPPS							
Cradle-to-material	111	662	27.5	923	1,723		
Fabrication-to-Grave	81.3	43.7	19.2	0	144		
Total	192	706	46.7	923	1,868	165	1,703

	Energy Category (percent)					
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit
Envelope Window Film						
PLA (2005)						
Cradle-to-material	22%	36%	2%	29%	89%	
Fabrication-to-Grave	5%	4%	2%	0%	11%	
Total	27%	40%	4%	29%	100%	4%
GPPS						
Cradle-to-material	6%	35%	1%	49%	92%	
Fabrication-to-Grave	4%	2%	1%	0%	8%	
Total	10%	38%	3%	49%	100%	9%

Source: Franklin Associates, a Division of ERG

production of non-fuel bearing materials, such as steel, that are taken into the transport process. *Fuel production and delivery energy* represents the energy that is used by the fuel producing industries in extracting the primary fuel from the earth, processing it and delivering it to the ultimate consumer." More information on these categories can be found in the Methodology report at PlasticsEurope's website: http://www.lca.plasticseurope.org/methodol.htm.

The PLA resin (cradle-to-resin) requires 89 percent of the total energy needed to make the envelope windows; whereas the resin transportation, drying, film extruding, and disposal require 11 percent of the total energy. The energy content of delivered fuel category requires the greatest amount of energy for the PLA envelope windows. It makes up 40 percent of PLA's total energy requirements. Although the feedstock energy category makes up 29 percent of the total energy for PLA, much of this feedstock energy represents the corn used as raw material. It is true that corn is used as a fuel (ethanol), but less than 7 percent of the corn grown in the U.S. in 2001 was used for fuel. The fuel use in transport energy makes up 4 percent of the PLA envelope window total energy.

Using the percent difference calculation as described above, the following conclusions can be made about a comparison of the total energy requirements of the envelope window film. The PLA 2005 envelope window requires the most total energy; however, the GPPS envelop window total energy is not significantly different from the PLA 2005 total energy.

Also included in Table 4-1 is the energy recovered from the combustion of 20 percent of post consumer envelope window film that is discarded, based on the national average percentage of municipal solid waste that is disposed by waste-to-energy combustion[3]. These are calculated using the higher heating value (HHV) of the resin used multiplied by 20 percent of the weight of the envelope windows disposed. The higher heating value of PLA is less than the petroleum-based resins; therefore, less combustion energy credit is given to the PLA envelope window film. The HHV for each resin is found in the Assumptions and Limitations section of this chapter. If combustion energy credit is given, the net energy conclusions do differ from the total energy conclusions regarding the PLA envelope windows. The PLA 2005 envelope window film requires significantly more energy than the GPPS envelope window net energy.

Table 4-2 shows the fuel sources of cradle-to-production energy by fossil and non-fossil fuel for 1,000,000 square inches of envelope window film. All four categories shown in Table 4-1 are included in the total energy results shown in the table. The fossil fuels include natural gas, petroleum and coal. These fuels are commonly used for direct combustion for process fuels and generation of electricity. Natural gas and petroleum are also used as raw material inputs for the production of petroleum-based plastics. Petroleum is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear, biomass, wind, and other (geothermal, etc.) shown in the table are used to generate electricity along with the fossil fuels. It should be noted that corn as feedstock energy is considered biomass and therefore in the non-fossil fuel.

The PLA envelope windows require 63 percent fossil fuel use, with the remainder coming from non-fossil sources. This is due to the feedstock energy, which is from corn, a non-fossil source. The GPPS envelope window film requires 95 percent fossil fuel use. The feedstock energy of the GPPS envelope window film makes up 52 percent of the fossil fuel required for those envelope windows.

Solid Waste

Solid waste details separated into cradle-to-material and fabrication-to-grave categories for the envelope window film are shown in Table 4-3. Solid waste is categorized into empirical categories, following the methodology of the PlasticsEurope database. According to the PlasticsEurope methodology report, "in the empirical system, the aim is to categorize solid waste into the smallest number of different categories that identify the type of disposal that has to be applied or the use, if any, to which the waste

3 Municipal Solid Waste in the United States: 2001 Facts and Figures. U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. August 2003.

Table 4-2

Energy by Fuel Type for Envelope Window Film
(MJ per 1 million square inches)

	Fuel Type			Fuel Type (percent)		
	Fossil Fuel	Non-fossil Fuel	Total	Fossil Fuel	Non-fossil Fuel	Total
Envelope Window Film						
PLA (2005)						
Cradle-to-material	1,092	709	1,801	53.8%	34.9%	88.7%
Fabrication-to-Grave	184	45.8	229	9.0%	2.3%	11.3%
Total	1,276	755	2,030	63%	37%	100%
GPPS						
Cradle-to-material	1,670	53.2	1,723	89%	3%	92%
Fabrication-to-Grave	112	32.7	144	6%	2%	8%
Total	1,782	85.9	1,868	95%	5%	100%

Source: Franklin Associates, a Division of ERG

can be put after appropriate processing". Also included in the solid waste table are post consumer wastes, which are the wastes discarded by the end users of the product.

No solid waste data were provided in Dr. Vink's journal paper for the PLA 2005 resin. The solid waste data shown for the PLA resin in Table 4-3 are estimated from the PLA (2006) dataset and do not include the solid waste credited for the purchase of wind energy credits. In many of the categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.

Post consumer wastes are the wastes discarded by the final users of the product. As we are including the U.S. average combustion of mixed municipal solid waste, 20 percent of that weight is combusted in waste-to-energy facilities and therefore subtracted out of the total post consumer wastes. The weight of post consumer wastes is directly related to the weight of a product. Therefore, heavier products produce more post consumer solid wastes. For the envelope window film, the PLA envelope window is the heaviest and so produces the most post consumer solid waste. The post consumer solid waste for the PLA envelope windows is approximately 20 percent greater than the post consumer solid waste for the GPPS envelope windows.

Environmental Emissions

Atmospheric and waterborne emissions for each system include emissions from processes and those associated with the combustion of fuels. Table 4-4 presents atmospheric emissions results and Table 4-6 shows waterborne emissions for 1,000,000 square inches of envelope window film. Table 4-5 gives a greenhouse gas summary for each of envelope window film analyzed. Atmospheric and waterborne emissions from the

Table 4-3

Solid Wastes for Envelope Window Film
(g per 1 million square inches)

	PLA (2005)			GPPS		
	Cradle-to-PLA resin	Fab-to-Grave	Total (1)	Cradle-to-HIPS resin	Fab-to-Grave	Total
Solid Waste Categories						
Plastic containers	0	0	0	0.020	0	0.020
Paper	0	4.22	4.22	0.44	3.53	3.96
Plastics	23.9	881	905	1.40	736	737
Metals	0	0.78	0.78	1.89	0.65	2.54
Putrescibles	0	0	0	0.060	0	0.060
Unspecified refuse	25.1	174	199	37.9	145	183
Mineral waste	440	9.61	450	37.9	8.02	45.9
Slags & ash	10.8	436	447	199	124	323
Mixed industrial	53.9	0	53.9	35.9	0	35.9
Regulated chemicals	106	6.59	112	81.7	5.50	87.2
Unregulated chemicals	27.1	3.45	30.6	57.8	2.88	60.7
Construction waste	0.048	0.017	0.064	1.52	0.014	1.53
Waste to incinerator	0	1.18	1.18	498	0.98	499
Inert chemical	0.024	0	0.024	53.8	0	53.8
Wood waste	0	6.74	6.74	0.020	5.62	5.64
Wooden pallets	0	0	0	0.040	0	0.040
Waste to recycling	0.024	0.38	0.41	6.38	0.32	6.70
Waste returned to mine	0.31	310	310	897	259	1,156
Tailings	232	1.44	234	152	1.20	153
Municipal solid waste	0	83.2	83.2	-41.9	69.4	27.6
Postconsumer solid waste	0	18,880	18,880	0	15,760	15,760

(1) No solid waste data were provided in Dr. Vink's journal paper for the PLA(2005) resin. The data shown for the resin is estimated from the PLA(2006) dataset and does not include the solid waste credited for the purchase of wind energy credits

Source: Franklin Associates, a Division of ERG

Franklin Associates fuel emissions model were limited to the emissions used in the PlasticsEurope database for consistency in reporting. A common practice in the PlasticsEurope database is the use of "<1" for emissions with less than 1 mg of emission per kg of product. In this analysis, the value "1" represents all "<1" values given by PlasticsEurope. This is the upper limit of these values, and so the values may be overstated by an unknown amount.

There are significant uncertainties with regard to the application of the data to the envelope window film systems. Because of these uncertainties, two systems' emissions of a given substance are not considered significantly different unless the percent difference exceeds 25 percent. (Percent difference is defined as the difference between two system totals divided by their average.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix D).

It is important to realize that interpretation of air and water emission data requires great care. The effects of the various emissions on humans and on the environment are

not fully known. The degree of potential environmental disruption due to environmental releases is not related to the weight of the releases in a simple way. No firm conclusions can be made from the various atmospheric or waterborne emissions that result from the product systems. Only comprehensive tables of the atmospheric and waterborne emissions are shown here.

Atmospheric Emissions. The predominant atmospheric emissions from the product systems include greenhouse gases (particularly carbon dioxide, methane, and nitrous oxide), nitrogen oxides, sulfur oxides, particulates (PM10), and hydrocarbons. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different air emissions or groups of air emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, *methane*, *aromatic hydrocarbons* and *polycyclic hydrocarbons* have been identified as separate groups with the more general heading of *hydrocarbons* being reserved for the remainder. When such a split has been introduced, there is no double counting. For example, if a benzene emission is included in the *aromatics* group, it is not included in the more general category of *hydrocarbons*."

Table 4-4 displays the individual atmospheric emissions for each of the envelope window film systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various atmospheric emissions that result from the envelope window film systems.

Greenhouse Gases. This analysis is not an LCIA (life cycle impact assessment) and thus the impacts of various environmental emissions are not evaluated. However, due to our understanding of the relationship between greenhouse gases and global warming, it is reasonable to develop conclusions based on the quantity of greenhouse gases generated by a system. Greenhouse gas emissions are expressed as carbon dioxide equivalents, which use global warming potentials developed by the International Panel on Climate Change (IPCC) to normalize the various greenhouse gases to an equivalent weight of carbon dioxide. The 100-year time horizon Global Warming Potentials for GHG was used for this analysis.

Greenhouse gas emissions are closely related to system fossil energy, and thus the trends observed for system fossil energy requirements also apply to system greenhouse gas emissions. The PLA 2005 envelope window film, although it produces a lower amount of CO_2 equivalents, is not significantly different from the GPPS envelope window CO_2 equivalent amount.

Table 4-4

Atmospheric Emissions of Envelope Window Film
(g per 1 million square inches)

	PLA (2005)	GPPS
Atmospheric Emissions		
dust (PM10)	234	23.3
CO	216	140
CO2	50,423	61,714
SOX as SO2	259	180
H2S	0.025	0.020
mercaptan	5.0E-05	0.020
NOX as NO2	393	139
NH3	0.15	0.040
Cl2	0.14	0.13
HCl	10.4	1.91
F2	2.4E-06	0.020
HF	0.41	0.058
hydrocarbons not specified elsewhere	47.6	59.3
aldehyde (-CHO)	0.043	0.038
organics	1.83	4.62
Pb+compounds as Pb	2.2E-04	0.020
Hg+compounds as Hg	4.3E-05	0.020
metals not specified elsewhere	0.020	0.060
H2SO4	3.2E-04	0.020
N2O	8.86	0.062
H2	4.33	1.80
dichloroethane (DCE) C2H4Cl2	0.0057	0.025
vinyl chloride monomer (VCM)	0.0035	0.023
CFC/HCFC/HFC not specified elsewhere	1.2E-07	0.020
organo-chlorine not specified elsewhere	0.25	0.032
HCN	0	0.020
CH4	416	623
aromatic HC not specified elsewhere	0.055	0.64
polycyclic hydrocarbons (PAH)	8.5E-06	0.060
NMVOC	8.51	1.69
CS2	0	0.020
methylene chloride CH2Cl2	1.7E-04	0.020
Cu+compounds as Cu	1.0E-05	0.020
As+compounds as As	2.0E-04	0.020
Cd+compounds as Cd	3.2E-05	0.020
Ag+compounds as Ag	0	0.020
Zn+compounds as Zn	5.3E-05	0.020
Cr+compounds as Cr	1.4E-04	0.040
Se+compounds as Se	5.7E-04	0.020
Ni+compounds as Ni	7.8E-04	0.060

Table 4-4 (Cont'd)

Atmospheric Emissions of Envelope Window Film
(g per 1 million square inches)

	PLA (2005)	GPPS
Atmospheric Emissions		
Sb+compounds as Sb	1.5E-05	0.020
ethylene C2H4	0.012	0.15
oxygen	0	0.020
asbestos	0	0.020
dioxin/furan as Teq	3.5E-08	0.020
benzene C6H6	0.018	0.46
toluene C7H8	0.025	0.083
xylenes C8H10	0.015	0.022
ethylbenzene C8H10	0.0019	0.80
HCFC-22 CHClF2	0	0.020
styrene	5.0E-09	1.50
propylene	0.0024	0.10
Fe+compounds as Fe	5.5E-05	0
Co+compounds as Co	8.8E-05	1.0E-05
V+compounds as V	2.9E-04	0
Al+compounds as Al	-0.10	0
B+compounds as B	1.2E-04	0
Manganese	2.7E-04	2.0E-05
Molybdenum	2.4E-06	0
Corn dust	1.79	0
Tin	1.2E-05	0
Titanium	2.4E-06	0
Barium	0.0084	0
Beryllium	9.5E-06	3.2E-07
Bromine	1.0E-04	0
Cyanide (unspecified)	2.2E-05	1.4E-08
Fluoride (unspecified)	4.0E-05	9.8E-07
Helium	0.0091	0
VOC (volatile organic compou	0.0058	0
Dust (PM 2.5)	0.36	0
Dust (unspecified)	3.21	0.14
Ethanol	10.9	0
Lactic acid	0.021	0
Particles (< 2.5 um)	-0.50	0
Particles (> 10 um)	-6.10	0
Particles (<10 and > 2.5 um)	-5.46	0

Source: Franklin Associates, a Division of ERG

Table 4-5

Greenhouse Gas Summary for Envelope Window Film
(g carbon dioxide equivalents per 1 million square inches)

	PLA (2005)	GPPS
CO2	50,423	61,714
N2O	2,622	18.3
CFC/HCFC/HFC not specified elsewhere	2.0E-04	33.9
CH4	9,565	14,326
methylene chloride CH2Cl2	0.0017	0.20
HCFC-22 CHClF2	0	33.9
Total	62,610	76,126

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, nitrous oxide--296, CFC/HCFCs--1700, methane--23, methylene chloride--10, HCFC22--1700.

Source: Franklin Associates, a Division of ERG

Waterborne Emissions. The predominant waterborne emissions from the container systems include dissolved solids, suspended solids, COD (chemical oxygen demand), BOD (biological oxygen demand), chlorides, and various metals. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different water emissions or groups of water emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, some specific metal ions are identified separately from the more general heading of metals. When such a split has been introduced, there is no double counting. For example, if a Na+ emission is identified, it is not included in the more general category of *metals (unspecified)*. However, some operators may not necessarily have reported separately all of the metals specifically identified elsewhere in the table. As a consequence, the category *metals (unspecified)* may well include some metals that were specifically identified by other companies and are included under the appropriate specific heading elsewhere in the table."

Table 4-6 displays the individual waterborne emissions for each of the envelope window film systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various waterborne emissions that result from the envelope window film systems.

CONCLUSIONS

A life cycle inventory (LCI) is an environmental profile that expresses environmental burdens from the perspective of energy consumption, solid waste generation, atmospheric emissions, and waterborne emissions. This LCI evaluated envelope window film systems and found that three types of environmental burdens were helpful in distinguishing the LCI results: 1) energy requirements, 2) solid waste generation, and 3) greenhouse gas emissions. The LCI conclusions for each of these categories are summarized below.

Energy Requirements

- The PLA 2005 envelope window requires the most total energy; however, the GPPS envelop window total energy is not significantly different from the PLA 2005 total energy.
- If combustion energy credit is given, the net energy conclusions do differ (due to the different HHVs and weights of envelope windows) from the total energy conclusions regarding the PLA envelope windows as follows:
  - The PLA 2005 envelope window film requires significantly more energy than the GPPS envelope window net energy.
  - The GPPS envelope windows require more fossil fuel than the PLA envelope windows. This is due in a large part to the feedstock energy of the GPPS envelope windows.

Solid Waste Generation

- In many of the empirical solid waste categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.
- The PLA envelope window film is the heaviest and so produces the most post consumer solid waste.

Greenhouse Gas Emissions

- The PLA 2005 envelope window film, although it produces a lower amount of CO_2 equivalents, is not significantly different from the GPPS envelope window CO_2 equivalent amount.

Table 4-6

Waterborne Emissions of Envelope Window Film
(g per 1 million square inches)

	PLA (2005)	GPPS
Waterborne Wastes		
COD	154	18.0
BOD	25.9	1.02
Pb+compounds as Pb	0.0025	0.021
Fe+compounds as Fe	1.04	0.30
Na+compounds as Na	63.5	21.1
acid as H+	0.026	0.11
NO3-	28.8	0.14
Hg+compounds as Hg	3.9E-06	0.020
ammonium compounds as NH4+	0.055	0.29
Cl-	209	72.3
CN-	1.2E-05	0.020
F-	0.097	0.020
S+sulphides as S	1.9E-04	0.020
dissolved organics (non-hydrocarbon)	0.020	0.19
suspended solids	89.9	11.0
detergent/oil	0.12	0.53
hydrocarbons not specified elsewhere	0.038	0.32
organo-chlorine not specified elsewhere	4.8E-05	0.020
dissolved chlorine	4.3E-05	0.020
phenols	0.0024	0.021
dissolved solids not specified elsewhere	207	82.6
P+compounds as P	0.29	0.060
other nitrogen as N	2.03	0.089
other organics not specified elsewhere	0.020	0.024
SO4--	4.06	8.11
dichloroethane (DCE)	0	0.020
vinyl chloride monomer (VCM)	2.4E-06	0.020
K+compounds as K	0.029	0.020
Ca+compounds as Ca	17.5	5.53
Mg+compounds as Mg	2.85	1.05
Cr+compounds as Cr	0.010	0.024
ClO3--	0.030	0.044
BrO3--	7.2E-06	0.020

Table 4-6 (Cont'd)

Waterborne Emissions of Envelope Window Film
(g per 1 million square inches)

	PLA (2005)	GPPS
Waterborne Wastes		
TOC	37.5	0.85
AOX	4.8E-06	0.020
Al+compounds as Al	0.35	0.16
Zn+compounds as Zn	0.0083	0.023
Cu+compounds as Cu	0.0013	0.040
Ni+compounds as Ni	0.0012	0.040
CO3--	0.049	2.43
As+compounds as As	0.0012	0.020
Cd+compounds as Cd	1.8E-04	0.020
Mn+compounds as Mn	0.011	0.022
organo-tin as Sn	0	0.020
SO3--	0	0.020
Ag+compounds as Ag	0.0094	0.0034
Ba+compounds Ba	4.82	1.94
Sr+compounds as Sr	0.25	0.11
V+compounds as V	1.2E-04	4.5E-05
organo-silicon	0	0.020
benzene	0.0075	0.023
dioxin/furan as Teq	8.6E-07	0.020
Mo+compounds as Mo	1.1E-04	0.020
Ca++	5.92	0
PO4(-3)	0.0058	0
Chromium +III	1.8E-04	0
Chromium +IV	1.2E-05	0
Heavy metals unspecified	0.80	0.091
Selenium	1.3E-04	2.0E-05
Titanium	0.0034	0.0014
Chlorine dissolved	1.2E-04	0
Fluorine	2.9E-05	0
Neutral salts	6.1E-04	0
halogenated organics	0.0019	4.7E-06

Source: Franklin Associates, a Division of ERG

CHAPTER 5

ENERGY AND ENVIRONMENTAL RESULTS FOR 10,000 FOAM MEAT TRAYS

INTRODUCTION

This chapter focuses on foam meat trays. Three plastic resins used to produce foam meat trays are modeled: PLA (polylactide) and GPPS (general-purpose polystyrene).

In order to express the results on an equivalent basis, a functional unit of equivalent consumer use was chosen for the foam meat trays in this analysis. The basis for this analysis is 10,000 foam meat trays. The foam meat tray (#2 size) in this analysis is the only product in this analysis where PLA is not already established in the market. Trials are being performed on PLA foam to be used for foam meat trays by various manufacturers. NatureWorks, the company producing PLA resin, estimated that their PLA foam meat tray is five percent heavier than the corresponding polystyrene foam (GPPS foam) meat tray. One company provided weights for the GPPS foam meat tray. The weights of the foam meat trays are displayed in Table 1-1 of the Introduction. Figures 5-1 and 5-2 display flow diagrams of the production of the two resins analyzed in this analysis. Figure 5-3 shows the overall life cycle of the foam meat trays analyzed in this report.

No secondary packaging or films used with the trays are considered in this analysis; only the primary product is analyzed. Transportation, filling, and use of the meat trays by consumers are assumed to be equivalent for all resin systems and are not included in this study. Environmental burdens associated with end-of-life management of the meat trays are not part of the scope of this analysis. Only landfilling and combustion of the meat trays are analyzed for end-of-life management. Other end-of-life scenarios are possible, but the goal of this analysis is to analyze each material used to produce the meat trays.

ASSUMPTIONS AND LIMITATIONS

Key assumptions of the LCI of foam meat trays are as follows:

- NatureWorks, the company producing PLA resin, estimated that their PLA foam meat tray is five percent heavier than the corresponding polystyrene foam (GPPS foam) meat tray. One company provided weights for the GPPS foam meat tray. Meat tray weights will vary by producer.

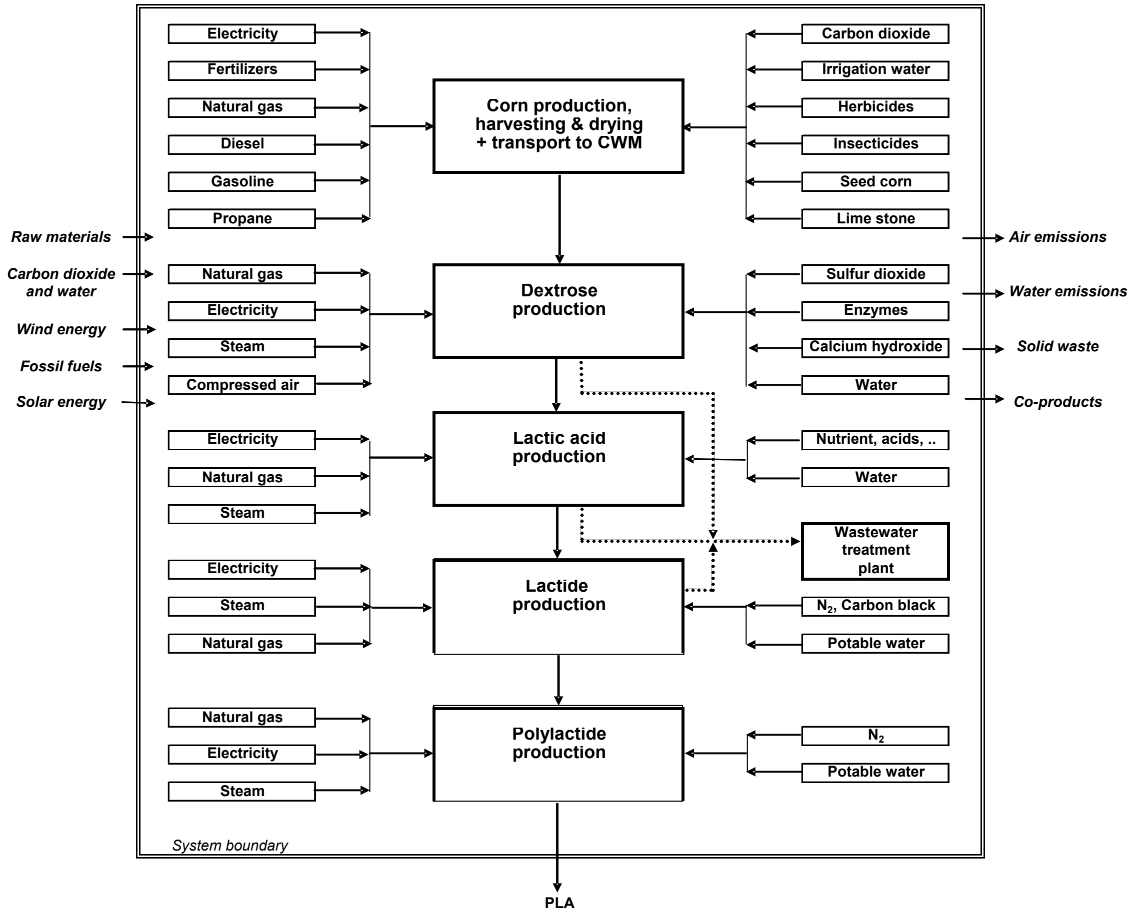

Figure 5-1. Simplified flow diagram and system boundary for the NatureWorks PLA resin production system. This flow diagram was taken from the 2006 draft journal paper provided by Dr. Erwin Vink of NatureWorks, LLC.

- The following distances and modes were used for each resin type:
  - PLA—560 ton-miles by combination truck
  - GPPS foam—107 ton-miles by combination truck, 107 ton-miles by rail
- The disposal of the products includes landfilling of post consumer products, as well as a 20 percent waste-to-energy combustion energy credit for the incineration of post consumer products in mixed municipal solid waste. Although it is true that most of the petroleum-based plastic can be recycled and PLA is available for composting, only a very small percentage of meat trays will actually get into the recycling and composting streams.
- The higher heating values used for the resins analyzed in this chapter are PLA—19 MJ/kg and GPPS—40.3 MJ/kg.

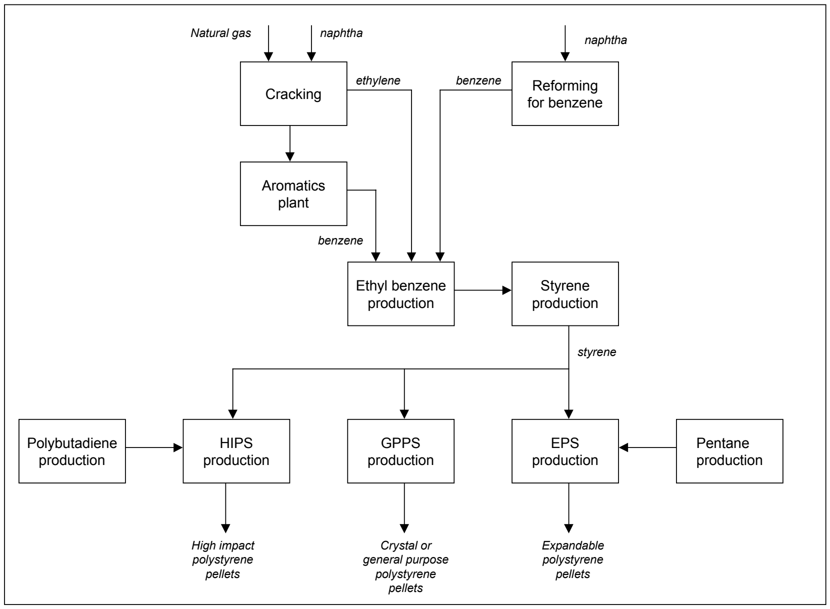

Figure 5-2. Flow diagram for the production of polystyrene resins. This flow diagram was taken from the report, **Eco-profiles of the European Plastics Industry: Polystyrene (High-Impact) (HIPS)**, PlasticsEurope, updated June, 2005.

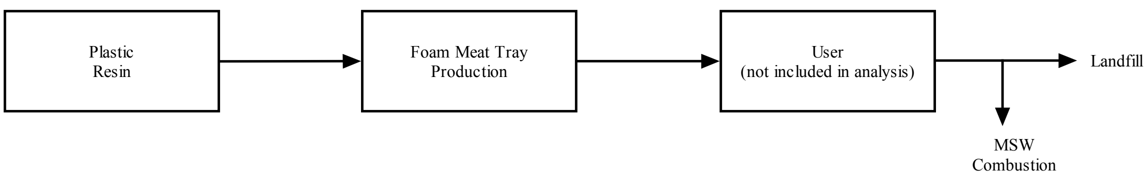

Figure 5-3. Flow diagram of the life cycle of foam meat trays. Transportation to user and use phase are not included in this analysis.

RESULTS

If the energy or post consumer solid waste of one system is 10 percent different from another, it can be concluded that the difference is significant. If the weight of industrial solid waste, atmospheric emissions or waterborne emissions of a system is 25 percent different from another, it can be concluded that the difference is significant. Percent difference is defined as the difference between two values divided by the average of the two values. (See Appendix D for an explanation of this certainty range.)

Energy Results

The energy results separated into cradle-to-material and fabrication-to-grave categories for 10,000 foam meat trays are shown in Tables 5-1 and 5-2. Cradle-to-grave total energy for each meat tray in Table 5-1 is separated into fuel production and delivery, energy content of delivered fuel, fuel use in transport, and feedstock energy. Table 5-1 also has a column that shows an energy credit for the energy recovered from waste-to

Table 5-1

Energy by Category for Foam Meat Trays
(MJ per 10,000 meat trays)

	Energy Category						
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit	Net Energy
Case ready meat trays							
PLA foam (2005)							
Cradle-to-material	1,024	1,693	99.5	1,399	4,215		
Fabrication-to-Grave	528	562	152	129	1,372		
Total	1,552	2,255	252	1,528	5,587	208	5,379
PS foam							
Cradle-to-material	789	2,274	42.3	2,593	5,698		
Fabrication-to-Grave	9.58	8.89	53.2	0	71.7		
Total	798	2,283	95.5	2,593	5,770	437	5,333

	Energy Category (percent)					
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit
Case ready meat trays						
PLA foam (2005)						
Cradle-to-material	18%	30%	2%	25%	75%	
Fabrication-to-Grave	9%	10%	3%	2%	25%	
Total	28%	40%	5%	27%	100%	4%
PS foam						
Cradle-to-material	14%	39%	1%	45%	99%	
Fabrication-to-Grave	0%	0%	1%	0%	1%	
Total	14%	40%	2%	45%	100%	8%

Source: Franklin Associates, a Division of ERG

energy incineration of 20 percent of the post consumer solid waste. Table 5-2 breaks the total energy into fossil and non-fossil fuel.

The categories used for the breakdown of the total energy are used in the PlasticsEurope database. The following definitions are quotes from the Methodology report for the PlasticsEurope database. "*Energy content of delivered fuel* represents the energy that is received by the final operator who consumes energy. *Feedstock energy* represents the energy of the fuel bearing materials that are taken into the system but used as materials rather than fuels. *Transport energy* refers to the energy associated with fuels consumed directly by the transport operations as well as any energy associated with the production of non-fuel bearing materials, such as steel, that are taken into the transport process. *Fuel production and delivery energy* represents the energy that is used by the fuel producing industries in extracting the primary fuel from the earth, processing it and delivering it to the ultimate consumer." More information on these categories can be found in the Methodology report at PlasticsEurope's website: http://www.lca.plasticseurope.org/methodol.htm.

The PLA resin (cradle-to-resin) requires 75 percent of the total energy needed to make the foam meat trays; whereas the resin transportation, drying, foaming and thermoforming, and disposal require 25 percent of the total energy. The energy content of delivered fuel category requires the greatest amount of energy for the PLA meat trays. It makes up 40 percent of PLA's total energy requirements. Although the feedstock energy category makes up 27 percent of the total energy for PLA, much of this feedstock energy represents the corn used as raw material. It is true that corn is used as a fuel (ethanol), but less than seven percent of the corn grown in the U.S. in 2001 was used for fuel. The fuel use in transport energy makes up five percent of the PLA total energy.

Using the percent difference calculation as described above, the following conclusions can be made about a comparison of the total energy requirements of foam meat trays. Although the PLA foam 2005 requires less total energy; it is not significantly different than the energy required for the GPPS foam meat tray.

Also included in Table 5-1 is the energy recovered from the combustion of 20 percent of post consumer trays that are discarded, based on the national average percentage of municipal solid waste (MSW) that is disposed by waste-to-energy (WTE) combustion[4]. These are calculated using the higher heating value of the resin used multiplied by 20 percent of the weight of the foam meat trays disposed. The higher heating value (HHV) of PLA is less than the petroleum-based resins; therefore, less combustion energy credit is given to the PLA meat trays. The HHV for each resin is found in the Assumptions and Limitations section of this chapter. If combustion energy credit is given, the net energy conclusions do *not* differ from the total energy conclusions regarding the PLA meat trays.

Table 5-2 shows the fuel sources of cradle-to-production energy by fossil and non-fossil fuel for 10,000 foam meat trays. All four categories shown in Table 5-1 are included in the total energy results shown in the table. The fossil fuels include natural gas, petroleum and coal. These fuels are commonly used for direct combustion for process fuels and generation of electricity. Natural gas and petroleum are also used as raw material inputs for the production of petroleum-based plastics. Petroleum is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear, biomass, wind, and other (geothermal, etc.) shown in the table are used to generate electricity along with the fossil fuels. It should be noted that corn as feedstock energy is considered biomass and therefore in the non-fossil fuel.

The PLA meat tray requires 66 percent fossil fuel use, with the remainder coming from non-fossil sources. This is due to the feedstock energy, which is from corn, a non-fossil source. The petroleum-based meat trays require greater than 90 percent fossil fuel use. The feedstock energy of the petroleum-based meat tray makes up 49 percent of the fossil fuel required for the GPPS foam meat trays.

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4 **Municipal Solid Waste in the United States: 2001 Facts and Figures.** U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. August 2003.

Table 5-2

Energy by Fuel Type for Foam Meat Trays
(MJ per 10,000 meat trays)

	Fuel Type			Fuel Type (percent)		
	Fossil Fuel	Non-fossil Fuel	Total	Fossil Fuel	Non-fossil Fuel	Total
Case ready meat trays						
PLA foam (2005)						
Cradle-to-material	2,556	1,659	4,215	46%	30%	75%
Fabrication-to-Grave	1,148	224	1,372	21%	4%	25%
Total	3,704	1,883	5,587	66%	34%	100%
PS foam						
Cradle-to-material	5,265	433	5,698	91%	8%	99%
Fabrication-to-Grave	71.0	0.63	71.7	1%	0%	1%
Total	5,336	433	5,770	92%	8%	100%

Source: Franklin Associates, a Division of ERG

Solid Waste

Solid waste details separated into cradle-to-material and fabrication-to-grave categories for 10,000 foam meat trays are shown in Table 5-3. Solid waste is categorized into empirical categories, following the methodology of the PlasticsEurope database. According to the PlasticsEurope methodology report, "in the empirical system, the aim is to categorize solid waste into the smallest number of different categories that identify the type of disposal that has to be applied or the use, if any, to which the waste can be put after appropriate processing". Also included in the solid waste table are post consumer wastes, which are the wastes discarded by the end users of the product.

No solid waste data were provided in Dr. Vink's journal paper for the PLA 2005 resin. The solid waste data shown for the PLA resin in Table 5-3 are estimated from the PLA (2006) dataset and do not include the solid waste credited for the purchase of wind energy credits. In many of the categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.

Post consumer wastes are the wastes discarded by the final users of the product. As we are including the U.S. average combustion of mixed municipal solid waste, 20 percent of that weight is combusted in waste-to-energy facilities and therefore subtracted out of the total post consumer wastes. The weight of post consumer wastes is directly related to the weight of a product. Therefore, heavier products produce more post consumer solid wastes. Due to the use of NatureWorks' estimate for the weight of the PLA foam meat tray, it is five percent heavier than the GPPS foam meat tray. This leads to a post consumer solid waste difference of five percent, which is not significantly different.

Table 5-3

Solid Wastes for Foam Meat Trays
(g per 10,000 meat trays)

	PLA foam (2005)			PS foam		
	Cradle-to-PLA resin	Fab-to-Grave	Total (1)	Cradle-to-GPPS resin	Fab-to-Grave	Total
Solid Waste Categories						
Plastic containers	0	0.0027	0.0027	0.052	0	0.052
Paper	0	1,634	1,634	1,566	0	1,566
Plastics	55.9	30.8	86.7	131	0	131
Metals	0	0.77	0.77	0.78	0	0.78
Putrescibles	0	0.0027	0.0027	0.052	0	0.052
Unspecified refuse	58.7	225	283	292	0	292
Mineral waste	1,030	191	1,221	235	0	235
Slags & ash	25.4	1,111	1,136	887	74.4	962
Mixed industrial	126	28.8	155	115	0	115
Regulated chemicals	247	27,638	27,885	26,622	0	26,622
Unregulated chemicals	63.5	153	217	485	0	485
Construction waste	0.11	0.0027	0.11	4.18	0	4.18
Waste to incinerator	0	82.8	82.8	1,357	0	1,357
Inert chemical	0.056	44.3	44.4	287	0	287
Wood waste	0	15.4	15.4	18.8	0	18.8
Wooden pallets	0	0.83	0.83	3.03	0	3.03
Waste to recycling	0.056	9.94	10.0	33.4	0	33.4
Waste returned to mine	0.73	621	622	2,975	0	2,975
Tailings	544	0.0027	544	418	0	418
Municipal solid waste	0	363	363	-428	0	-428
Postconsumer solid waste	0	43,840	43,840	0	41,760	41,760

(1) No solid waste data were provided in Dr. Vink's journal paper for the PLA(2005) resin. The data shown for the resin is estimated from the PLA(2006) dataset and does not include the solid waste credited for the purchase of wind energy credits.

Source: Franklin Associates, a Division of ERG

Environmental Emissions

Atmospheric and waterborne emissions for each system include emissions from processes and those associated with the combustion of fuels. Table 5-4 presents atmospheric emissions results and Table 5-6 shows waterborne emissions for 10,000 foam meat trays. Table 5-5 gives a greenhouse gas summary for each of the meat trays analyzed. Atmospheric and waterborne emissions from the Franklin Associates fuel emissions model were limited to the emissions used in the PlasticsEurope database for consistency in reporting. A common practice in the PlasticsEurope database is the use of "<1" for emissions with less than 1 mg of emission per kg of product. In this analysis, the value "1" represents all "<1" values given by PlasticsEurope. This is the upper limit of these values, and so the values may be overstated by an unknown amount.

There are significant uncertainties with regard to the application of the data to the meat tray systems. Because of these uncertainties, two systems' emissions of a given substance are not considered significantly different unless the percent difference exceeds 25 percent. (Percent difference is defined as the difference between two system totals divided by their average.) This minimum percent difference criterion was developed

based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix D).

It is important to realize that interpretation of air and water emission data requires great care. The effects of the various emissions on humans and on the environment are not fully known. The degree of potential environmental disruption due to environmental releases is not related to the weight of the releases in a simple way. No firm conclusions can be made from the various atmospheric or waterborne emissions that result from the product systems. Only comprehensive tables of the atmospheric and waterborne emissions are shown here.

Atmospheric Emissions. The predominant atmospheric emissions from the product systems include greenhouse gases (particularly carbon dioxide, methane, and nitrous oxide), nitrogen oxides, sulfur oxides, particulates (PM10), and hydrocarbons. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different air emissions or groups of air emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, *methane*, *aromatic hydrocarbons* and *polycyclic hydrocarbons* have been identified as separate groups with the more general heading of *hydrocarbons* being reserved for the remainder. When such a split has been introduced, there is no double counting. For example, if a benzene emission is included in the *aromatics* group, it is not included in the more general category of *hydrocarbons*."

Table 5-4 displays the individual atmospheric emissions for each of the meat tray systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various atmospheric emissions that result from the foam meat tray systems.

Greenhouse Gases. This analysis is not an LCIA (life cycle impact assessment) and thus the impacts of various environmental emissions are not evaluated. However, due to our understanding of the relationship between greenhouse gases and global warming, it is reasonable to develop conclusions based on the quantity of greenhouse gases generated by a system. Greenhouse gas emissions are expressed as carbon dioxide equivalents, which use global warming potentials developed by the International Panel on Climate Change (IPCC) to normalize the various greenhouse gases to an equivalent weight of carbon dioxide. The 100-year time horizon Global Warming Potentials for GHG was used for this analysis.

Greenhouse gas emissions are closely related to system fossil energy, and thus the trends observed for system fossil energy requirements also apply to system greenhouse gas emissions. The amount of CO_2 equivalents for the PLA 2005 meat tray is not significantly different from the amount of CO_2 equivalents for the GPPS foam meat tray. This is due to the fact that much of the fossil fuel used in the GPPS foam meat tray is

from feedstock energy, which is bound within the product and therefore does not produce greenhouse gases.

Waterborne Emissions. The predominant waterborne emissions from the container systems include dissolved solids, suspended solids, COD (chemical oxygen demand), BOD (biological oxygen demand), chlorides, and various metals. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different water emissions or groups of water emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, some specific metal ions are identified separately from the more general heading of metals. When such a split has been introduced, there is no double counting. For example, if a Na+ emission is identified, it is not included in the more general category of *metals (unspecified)*. However, some operators may not necessarily have reported separately all of the metals specifically identified elsewhere in the table. As a consequence, the category *metals (unspecified)* may well include some metals that were specifically identified by other companies and are included under the appropriate specific heading elsewhere in the table."

Table 5-6 displays the individual waterborne emissions for each of the meat tray systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various waterborne emissions that result from the foam meat tray systems.

CONCLUSIONS

A life cycle inventory (LCI) is an environmental profile that expresses environmental burdens from the perspective of energy consumption, solid waste generation, atmospheric emissions, and waterborne emissions. This LCI evaluated foam meat tray systems and found that three types of environmental burdens were helpful in distinguishing the LCI results: 1) energy requirements, 2) solid waste generation, and 3) greenhouse gas emissions. The LCI conclusions for each of these categories are summarized below.

Energy Requirements

- The PLA 2005 foam meat tray total energy is not significantly different from the GPPS foam meat tray.
- If combustion energy credit is given, the net energy conclusions do *not* differ from the total energy conclusions regarding the PLA meat tray.
- The GPPS foam meat trays require more fossil fuel than the PLA meat trays. This is due in a large part to the feedstock energy of the GPPS foam meat trays.

Table 5-4

Atmospheric Emissions of Foam Meat Trays
(g per 10,000 meat trays)

	PLA foam (2005)	PS foam
Atmospheric Emissions		
dust (PM10)	558	69.1
CO	536	286
CO2	153,487	182,763
SOX as SO2	950	786
H2S	0.11	0.10
mercaptan	0.0029	0.052
NOX as NO2	1,068	459
NH3	0.35	0.083
Cl2	0.012	0.052
HCl	24.1	5.27
F2	0.0027	0.052
HF	1.03	0.21
hydrocarbons not specified elsewhere	150,344	327
aldehyde (-CHO)	0.15	0.11
organics	4.55	12.0
Pb+compounds as Pb	0.0033	0.052
Hg+compounds as Hg	0.0028	0.052
metals not specified elsewhere	0.26	0.37
H2SO4	0.0035	0.052
N2O	20.8	0.21
H2	9.62	4.70
dichloroethane (DCE) C2H4Cl2	0.0028	0.052
vinyl chloride monomer (VCM)	0.0029	0.052
CFC/HCFC/HFC not specified elsewhere	0.0027	0.052
organo-chlorine not specified elsewhere	0.56	0.052
HCN	0.0027	0.052
CH4	1,391	2,095
aromatic HC not specified elsewhere	0.26	1.67
polycyclic hydrocarbons (PAH)	0.016	0.31
NMVOC	27.5	24.9
CS2	0.0027	0.052
methylene chloride CH2Cl2	0.0032	0.052
Cu+compounds as Cu	0.0028	0.052
As+compounds as As	0.0032	0.052
Cd+compounds as Cd	0.0028	0.052
Ag+compounds as Ag	0.0027	0.052
Zn+compounds as Zn	0.0029	0.052
Cr+compounds as Cr	0.0031	0.16
Se+compounds as Se	0.0041	0.052
Ni+compounds as Ni	0.0049	0.26
Sb+compounds as Sb	0.0028	0.052

Table 5-4 (cont'd)

Atmospheric Emissions of Foam Meat Trays
(g per 10,000 meat trays)

	PLA foam (2005)	PS foam
Atmospheric Emissions		
ethylene C2H4	0.0027	0.31
oxygen	0.0027	0.052
asbestos	0.0027	0.052
dioxin/furan as Teq	0.0027	0.052
benzene C6H6	0.051	0.90
toluene C7H8	0.071	0.12
xylenes C8H10	0.042	0.059
ethylbenzene C8H10	0.0078	0.26
HCFC-22 CHClF2	0.054	0.10
styrene	0.0027	1.93
propylene	0.013	0.27
Fe+compounds as Fe	1.3E-04	0
Co+compounds as Co	2.3E-04	3.6E-05
V+compounds as V	6.8E-04	0
Al+compounds as Al	-0.23	0
B+compounds as B	2.9E-04	0
Manganese	6.9E-04	7.1E-05
Molybdenum	5.6E-06	0
Corn dust	4.20	0
Tin	2.8E-05	0
Titanium	5.6E-06	0
Barium	0.020	0
Beryllium	2.3E-05	1.1E-06
Bromine	2.3E-04	0
Cyanide (unspecified)	5.2E-05	4.9E-08
Fluoride (unspecified)	9.6E-05	3.4E-06
Helium	0.021	0
VOC (volatile organic compou	0.014	0
Dust (PM 2.5)	0.83	0
Dust (unspecified)	7.86	0.48
Ethanol	25.5	0
Lactic acid	0.049	0
Particles (< 2.5 um)	-1.17	0
Particles (> 10 um)	-14.28	0
Particles (<10 and > 2.5 um)	-12.79	0

Source: Franklin Associates, a Division of ERG

Table 5-5

Greenhouse Gas Summary for Foam Meat Trays
(g carbon dioxide equivalents per 10,000 meat trays)

	PLA foam (2005)	PS foam
CO2	153,487	182,763
N2O	6,171	60.8
CFC/HCFC/HFC not specified elsewhere	4.66	88.7
CH4	32,001	48,181
methylene chloride CH2Cl2	0.032	0.52
HCFC-22 CHClF2	91.3	177
Total	191,755	231,272

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, nitrous oxide--296, CFC/HCFCs--1700, methane--23, methylene chloride--10, HCFC22--1700.

Source: Franklin Associates, a Division of ERG

Solid Waste Generation

- In many of the empirical solid waste categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.
- The PLA foam meat tray is five percent heavier than the GPPS foam meat tray. This leads to a post consumer solid waste difference of five percent, which is not significantly different.

Greenhouse Gas Emissions

- The amount of CO_2 equivalents for the PLA 2005 foam meat tray is not significantly different from the amount of CO_2 equivalents for the GPPS foam meat tray. This is due to the fact that much of the fossil fuel used in the GPPS foam meat tray is from feedstock energy, which is bound within the product and therefore does not produce greenhouse gases.

Table 5-6

Waterborne Emissions of Foam Meat Trays
(g per 10,000 meat trays)

	PLA foam (2005)	PS foam
Waterborne Wastes		
COD	346	115
BOD	60.8	11.1
Pb+compounds as Pb	0.011	0.055
Fe+compounds as Fe	3.22	1.04
Na+compounds as Na	198	75.5
acid as H+	0.14	0.52
NO3-	67.5	0.47
Hg+compounds as Hg	0.0028	0.052
ammonium compounds as NH4+	0.062	1.04
Cl-	641	241
CN-	0.0028	0.052
F-	0.23	0.053
S+sulphides as S	0.0034	0.052
dissolved organics (non-hydrocarbon)	0.18	0.57
suspended solids	235	125
detergent/oil	0.58	2.32
hydrocarbons not specified elsewhere	0.093	0.84
organo-chlorine not specified elsewhere	0.0029	0.052
dissolved chlorine	0.0028	0.052
phenols	0.011	0.055
dissolved solids not specified elsewhere	689	333
P+compounds as P	0.67	3.86
other nitrogen as N	5.10	0.52
other organics not specified elsewhere	0.061	0.068
SO4--	11.7	23.4
dichloroethane (DCE)	0.0027	0.052
vinyl chloride monomer (VCM)	0.0027	0.052
K+compounds as K	0.071	0.052
Ca+compounds as Ca	55.7	19.2
Mg+compounds as Mg	9.56	3.65
Cr+compounds as Cr	0.038	0.066
ClO3--	0.0063	0.052
BrO3--	0.0028	0.052
TOC	87.7	2.04
AOX	0.0028	0.052
Al+compounds as Al	1.23	0.54
Zn+compounds as Zn	0.031	0.064
Cu+compounds as Cu	0.0070	0.054
Ni+compounds as Ni	0.0068	0.054
CO3--	0.46	6.26
As+compounds as As	0.0069	0.054
Cd+compounds as Cd	0.0034	0.052
Mn+compounds as Mn	0.033	0.058
organo-tin as Sn	0.0027	0.052
SO3--	0	0.052
Ag+compounds as Ag	0.032	0.012
Ba+compounds Ba	16.7	6.75
Sr+compounds as Sr	0.83	0.36
V+compounds as V	4.1E-04	1.6E-04
organo-silicon	0.0027	0.052
benzene	0.028	0.11
dioxin/furan as Teq	0.0027	0.052
Mo+compounds as Mo	3.5E-04	0.052
Ca++	13.8	0
PO4(-3)	0.014	0
Chromium +III	4.3E-04	0
Chromium +IV	2.8E-05	0
Heavy metals unspecified	2.12	0.32
Selenium	3.6E-04	6.8E-05
Titanium	0.012	0.0047
Chlorine dissolved	2.8E-04	0
Fluorine	6.7E-05	0
Neutral salts	0.0014	0
halogenated organics	0.0044	1.6E-05

Source: Franklin Associates, a Division of ERG

CHAPTER 6

ENERGY AND ENVIRONMENTAL RESULTS FOR 10,000 12-OUNCE WATER BOTTLES

INTRODUCTION

This chapter focuses on 12-ounce water bottles. Two plastic resins used in the marketplace currently for water bottles are modeled: PLA (polylactide) and PET (polyethylene terephthalate).

In order to express the results on an equivalent basis, a functional unit of equivalent consumer use was chosen for the 12-ounce water bottles in this analysis. The basis for this analysis is 10,000 12-ounce water bottles. PET samples were purchased and weighed by Franklin Associates staff. A bottle producer provided the PLA water bottle weights. The weights of the water bottles are displayed in Table 1-1 of the Introduction. Figures 6-1 and 6-2 display flow diagrams of the production of the two resins analyzed in this analysis. Figure 6-3 shows the overall life cycle of the water bottles analyzed in this report.

No secondary packaging is considered in this analysis; only the primary product is analyzed. Transportation, filling, and use of the water bottles by consumers are assumed to be equivalent for all resin systems and are not included in this study. Environmental burdens associated with end-of-life management of the water bottles are not part of the scope of this analysis. Only landfilling and combustion of the water bottles are analyzed for end-of-life management. Other end-of-life scenarios are possible, but the goal of this analysis is to analyze each material used to produce the water bottles.

ASSUMPTIONS AND LIMITATIONS

Key assumptions of the LCI of water bottles are as follows:

- PET water bottle samples were purchased and weighed by Franklin Associates staff. One bottle producer provided the PLA water bottle weights. Water bottle weights will vary by producer.
- The following distances and modes were used for each resin type:
  - PLA—425 ton-miles by combination truck
  - PET—96 ton-miles by combination truck, 96 ton-miles by rail
- The disposal of the products includes landfilling of post consumer products, as well as a 20 percent waste-to-energy (WTE) combustion energy credit for the incineration of post consumer products in mixed municipal solid waste. Although it is true that PET can be recycled and PLA is available for composting, this study focuses on analyzing the materials and fabrication processes.

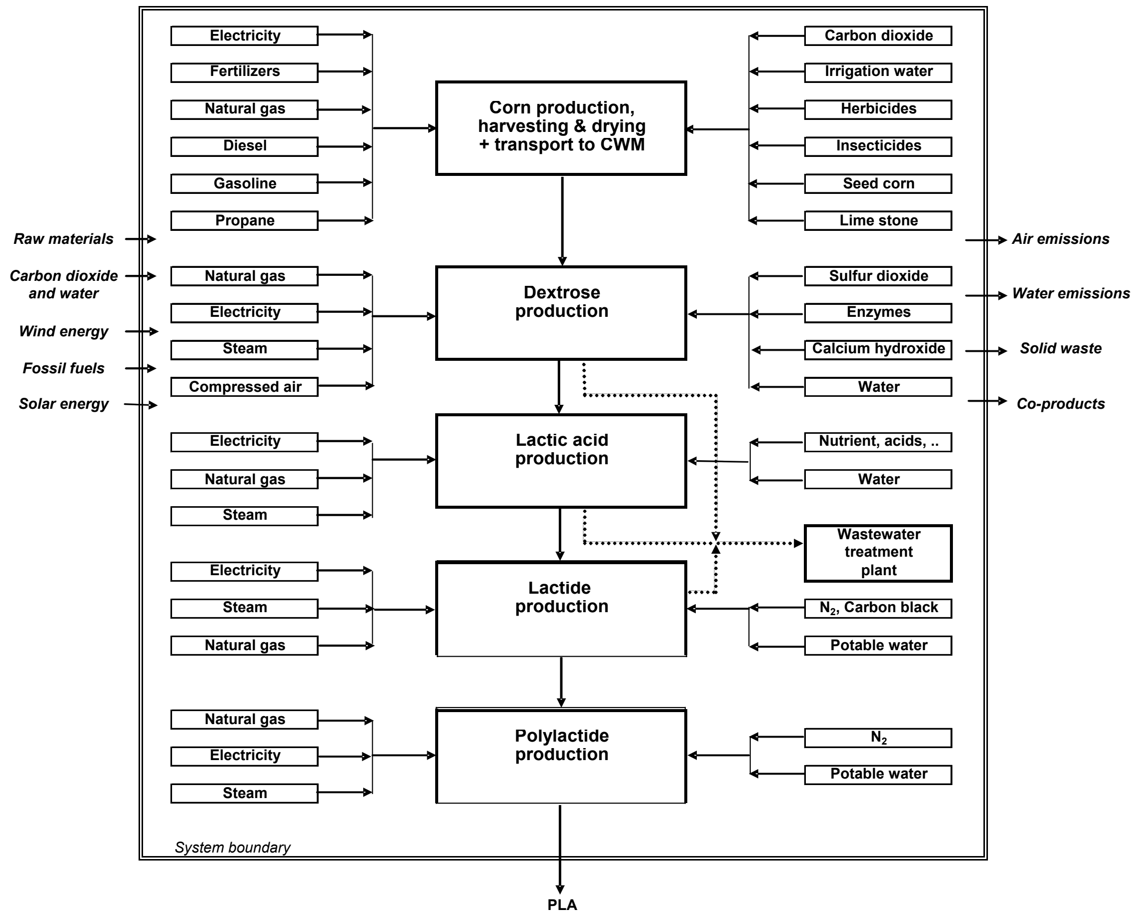

Figure 6-1. Simplified flow diagram and system boundary for the NatureWorks PLA resin production system. This flow diagram was taken from the 2006 draft journal paper provided by Dr. Erwin Vink of NatureWorks, LLC.

- The higher heating values used for the resins analyzed in this chapter are PLA—19 MJ/kg and PET—26 MJ/kg.

RESULTS

If the energy or post consumer solid waste of one system is 10 percent different from another, it can be concluded that the difference is significant. If the weight of industrial solid waste, atmospheric emissions or waterborne emissions of a system is 25 percent different from another, it can be concluded that the difference is significant. Percent difference is defined as the difference between two values divided by the average of the two values. (See Appendix D for an explanation of this certainty range.)

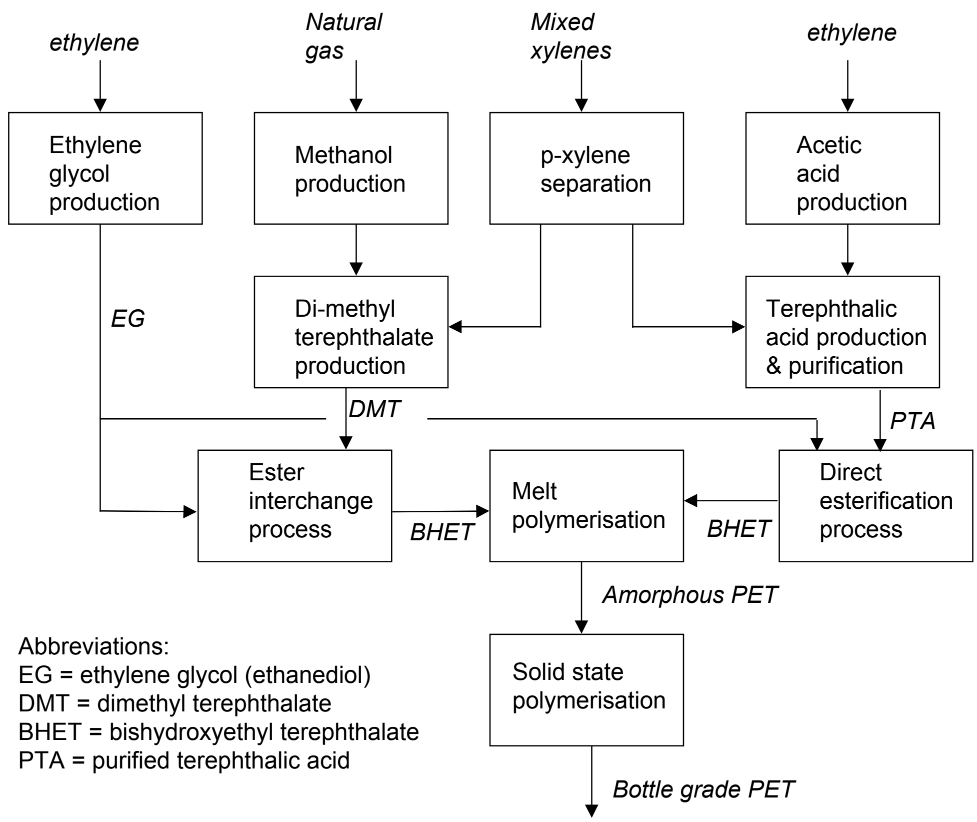

Figure 6-2. Flow diagram showing the two routes to polyethylene terephthalate (PET) resin. This flow diagram was taken from the report, **Eco-profiles of the European Plastics Industry: Polyethylene Terephthalate (PET) (Bottle grade)**, PlasticsEurope, updated March, 2005.

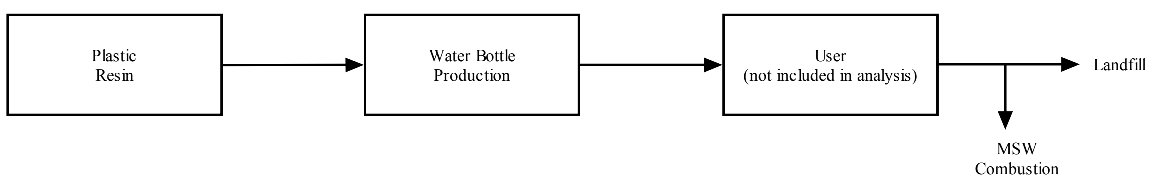

Figure 6-3. Flow diagram of the life cycle of 12-ounce water bottles. Transportation to user and use phase are not included in this analysis.

Energy Results

The energy results separated into cradle-to-material and fabrication-to-grave categories for 10,000 12-ounce water bottles are shown in Tables 6-1 and 6-2. Cradle-to-grave total energy for each water bottle in Table 6-1 is separated into fuel production and delivery, energy content of delivered fuel, fuel use in transport, and feedstock energy. Table 6-1 also has a column that shows an energy credit for the energy recovered from waste-to-energy incineration of 20 percent of the post consumer solid waste. Table 6-2 breaks the total energy into fossil and non-fossil fuel.

The categories used for the breakdown of the total energy are used in the PlasticsEurope database. The following definitions are quotes from the Methodology report for the PlasticsEurope database. "*Energy content of delivered fuel* represents the energy that is received by the final operator who consumes energy. *Feedstock energy* represents the energy of the fuel bearing materials that are taken into the system but used as materials rather than fuels. *Transport energy* refers to the energy associated with fuels consumed directly by the transport operations as well as any energy associated with the production of non- fuel bearing materials, such as steel, that are taken into the transport process. *Fuel production and delivery energy* represents the energy that is used by the fuel producing industries in extracting the primary fuel from the earth, processing it and delivering it to the ultimate consumer." More information on these categories can be found in the Methodology report at PlasticsEurope's website: http://www.lca.plasticseurope.org/methodol.htm.

The PLA resin (cradle-to-resin) requires 80 percent of the total energy needed to make the water bottles; whereas the resin transportation, drying, blow molding, and disposal require 20 percent of the total energy. The energy content of delivered fuel category requires the greatest amount of energy for the PLA water bottles. It makes up 39 percent of PLA's total energy requirements. Although the feedstock energy category makes up 27 percent of the total energy for PLA, much of this feedstock energy represents the corn used as raw material. It is true that corn is used as a fuel (ethanol), but less than seven percent of the corn grown in the U.S. in 2001 was used for fuel. The fuel use in transport energy makes up four percent of the PLA water bottles total energy.

Using the percent difference calculation as described above, the following conclusions can be made about a comparison of the total energy requirements of the water bottles. The PET water bottles require the most total energy; however, its total energy is not significantly different than the PLA 2005 total energy.

Also included in Table 6-1 is the energy recovered from the combustion of 20 percent of post consumer water bottles that are discarded, based on the national average percentage of municipal solid waste (MSW) that is disposed by waste-to-energy (WTE) combustion[5]. These are calculated using the higher heating value of the resin used multiplied by 20 percent of the weight of the water bottles disposed. The higher heating value (HHV) of PLA is less than the PET; therefore, less combustion energy credit is given to the PLA water bottles. The HHV for each resin is found in the Assumptions and Limitations section of this chapter. If combustion energy credit is given, the net energy conclusions do *not* differ from the total energy conclusions regarding the PLA water bottles.

Table 6-2 shows the fuel sources of cradle-to-production energy by fossil and non-fossil fuel for 10,000 12-ounce water bottles. All four categories shown in Table 6-1 are included in the total energy results shown in the table. The fossil fuels include natural gas, petroleum and coal. These fuels are commonly used for direct combustion for

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5 **Municipal Solid Waste in the United States: 2001 Facts and Figures.** U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response. August 2003.

Table 6-1

Energy by Category for 12-ounce Water Bottles
(MJ per 10,000 12-ounce water bottles)

	Energy Category						
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit	Net Energy
12-ounce water bottle							
PLA (2005)							
Cradle-to-material	3,847	6,359	374	5,256	15,836		
Fabrication-to-Grave	2,232	1,277	446	0	3,955		
Total	6,079	7,636	820	5,256	19,791	798	18,993
PET							
Cradle-to-material	5,725	7,174	132	8,071	21,102		
Fabrication-to-Grave	35.8	34.6	197	0	268		
Total	5,760	7,209	329	8,071	21,370	1,096	20,274

	Energy Category (percent)					
	Fuel Production and Delivery	Energy Content of Delivered Fuel	Fuel Use in Transport	Feedstock Energy	Total	Combustion Energy Credit
12-ounce water bottle						
PLA (2005)						
Cradle-to-material	19%	32%	2%	27%	80%	
Fabrication-to-Grave	11%	6%	2%	0%	20%	
Total	31%	39%	4%	27%	100%	4%
PET						
Cradle-to-material	27%	34%	1%	38%	99%	
Fabrication-to-Grave	0%	0%	1%	0%	1%	
Total	27%	34%	2%	38%	100%	5%

Source: Franklin Associates, a Division of ERG

process fuels and generation of electricity. Natural gas and petroleum are also used as raw material inputs for the production of petroleum-based plastics. Petroleum is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear, biomass, wind, and other (geothermal, etc.) shown in the table are used to generate electricity along with the fossil fuels. It should be noted that corn as feedstock energy is considered biomass and therefore in the non-fossil fuel.

The PLA water bottles require 64 percent fossil fuel use, with the remainder coming from non-fossil sources. This is due to the feedstock energy, which is from corn, a non-fossil source. The PET water bottles require 89 percent fossil fuel use. The feedstock energy of the PET water bottles makes up 42 percent of the fossil fuel required for those water bottles.

Solid Waste

Solid waste details separated into cradle-to-material and fabrication-to-grave categories for 10,000 12-ounce water bottles are shown in Table 6-3. Solid waste is categorized into empirical categories, following the methodology of the PlasticsEurope

Table 6-2

Energy by Fuel Type for 12-ounce Water Bottles
(MJ per 10,000 12-ounce water bottles)

	Fuel Type			Fuel Type (percent)		
	Fossil Fuel	Non-fossil Fuel	Total	Fossil Fuel	Non-fossil Fuel	Total
12-ounce water bottle						
PLA (2005)						
Cradle-to-material	9,603	6,233	15,836	49%	31%	80%
Fabrication-to-Grave	3,038	917	3,955	15%	5%	20%
Total	12,641	7,150	19,791	64%	36%	100%
PET						
Cradle-to-material	18,771	2,330	21,102	88%	11%	99%
Fabrication-to-Grave	266	2.36	268	1%	0%	1%
Total	19,037	2,333	21,370	89%	11%	100%

Source: Franklin Associates, a Division of ERG

Table 6-3

Solid Wastes for 12-ounce Water Bottles
(g per 10,000 12-ounce water bottles)

	PLA (2005)			PET		
Solid Waste Categories	Cradle-to-PLA resin	Fab-to-Grave	(1) Total	Cradle-to-HIPS resin	Fab-to-Grave	Total
Plastic containers	0	0	0	0.20	0	0.20
Paper	0	0	0	0.20	0	0.20
Plastics	210	0	210	467	0	467
Metals	0	0	0	0.20	0	0.20
Putrescibles	0	0	0	0.20	0	0.20
Unspecified refuse	221	14.7	235	325	0	325
Mineral waste	3,869	7.35	3,876	91.4	0	91.4
Slags & ash	95.3	5,691	5,787	8,323	278	8,601
Mixed industrial	474	14.7	489	305	0	305
Regulated chemicals	928	29.4	958	609	0	609
Unregulated chemicals	239	14.7	253	1,827	0	1,827
Construction waste	0.42	0	0.42	11.0	0	11.0
Waste to incinerator	0	0	0	162	0	162
Inert chemical	0.21	0	0.21	386	0	386
Wood waste	0	0	0	0.20	0	0.20
Wooden pallets	0	0	0	0.20	0	0.20
Waste to recycling	0.21	0	0.21	36.5	0	36.5
Waste returned to mine	2.73	7,791	7,794	22,330	0	22,330
Tailings	2,043	0.29	2,043	1.02	0	1.02
Municipal solid waste	0	1,485	1,485	-3,451	0	-3,451
Postconsumer solid waste	0	168,000	168,000	0	162,400	162,400

(1) No solid waste data were provided in Dr. Vink's journal paper for the PLA(2005) resin. The data shown for the resin is estimated from the PLA(2006) dataset and does not include the solid waste credited for the purchase of wind energy credits

Source: Franklin Associates, a Division of ERG

database. According to the PlasticsEurope methodology report, “in the empirical system, the aim is to categorize solid waste into the smallest number of different categories that identify the type of disposal that has to be applied or the use, if any, to which the waste can be put after appropriate processing”. Also included in the solid waste table are post consumer wastes, which are the wastes discarded by the end users of the product.

No solid waste data were provided in Dr. Vink’s journal paper for the PLA 2005 resin. The solid waste data shown for the PLA resin in Table 6-3 are estimated from the PLA (2006) dataset and do not include the solid waste credited for the purchase of wind energy credits. In many of the categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.

Post consumer wastes are the wastes discarded by the final users of the product. As we are including the U.S. average combustion of mixed municipal solid waste, 20 percent of that weight is combusted in waste-to-energy facilities and therefore subtracted out of the total post consumer wastes. The weight of post consumer wastes is directly related to the weight of a product. Therefore, heavier products produce more post consumer solid wastes. For the water bottles, the PLA water bottle is the heaviest and so produces the more post consumer solid waste; however, there is only a three percent difference between the PLA and PET post consumer solid waste, and so they are not considered significantly different.

Environmental Emissions

Atmospheric and waterborne emissions for each system include emissions from processes and those associated with the combustion of fuels. Table 6-4 presents atmospheric emissions results and Table 6-6 shows waterborne emissions for 10,000 12-ounce water bottles. Table 6-5 gives a greenhouse gas summary for each of the water bottles analyzed. Atmospheric and waterborne emissions from the Franklin Associates fuel emissions model were limited to the emissions used in the PlasticsEurope database for consistency in reporting. A common practice in the PlasticsEurope database is the use of “<1” for emissions with less than 1 mg of emission per kg of product. In this analysis, the value “1” represents all “<1” values given by PlasticsEurope. This is the upper limit of these values, and so the values may be overstated by an unknown amount.

There are significant uncertainties with regard to the application of the data to the water bottle systems. Because of these uncertainties, two systems’ emissions of a given substance are not considered significantly different unless the percent difference exceeds 25 percent. (Percent difference is defined as the difference between two system totals divided by their average.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix D).

It is important to realize that interpretation of air and water emission data requires great care. The effects of the various emissions on humans and on the environment are

not fully known. The degree of potential environmental disruption due to environmental releases is not related to the weight of the releases in a simple way. No firm conclusions can be made from the various atmospheric or waterborne emissions that result from the product systems. Only comprehensive tables of the atmospheric and waterborne emissions are shown here.

Atmospheric Emissions. The predominant atmospheric emissions from the product systems include greenhouse gases (particularly carbon dioxide, methane, and nitrous oxide), nitrogen oxides, sulfur oxides, particulates (PM10), and hydrocarbons. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different air emissions or groups of air emissions are empirical and reflect the ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, *methane*, *aromatic hydrocarbons* and *polycyclic hydrocarbons* have been identified as separate groups with the more general heading of *hydrocarbons* being reserved for the remainder. When such a split has been introduced, there is no double counting. For example, if a benzene emission is included in the *aromatics* group, it is not included in the more general category of *hydrocarbons*."

Table 6-4 displays the individual atmospheric emissions for each of the water bottle systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various atmospheric emissions that result from the water bottle systems.

Greenhouse Gases. This analysis is not an LCIA (life cycle impact assessment) and thus the impacts of various environmental emissions are not evaluated. However, due to our understanding of the relationship between greenhouse gases and global warming, it is reasonable to develop conclusions based on the quantity of greenhouse gases generated by a system. Greenhouse gas emissions are expressed as carbon dioxide equivalents, which use global warming potentials developed by the International Panel on Climate Change (IPCC) to normalize the various greenhouse gases to an equivalent weight of carbon dioxide. The 100-year time horizon Global Warming Potentials for GHG was used for this analysis.

Greenhouse gas emissions are closely related to system fossil energy, and thus the trends observed for system fossil energy requirements also apply to system greenhouse gas emissions. The CO_2 equivalent amount for the PLA 2005 water bottles is significantly less than the PET water bottles' CO_2 equivalent amount.

Waterborne Emissions. The predominant waterborne emissions from the container systems include dissolved solids, suspended solids, COD (chemical oxygen demand), BOD (biological oxygen demand), chlorides, and various metals. According to the PlasticsEurope methodology, "within the tables, the categories used to identify the different water emissions or groups of water emissions are empirical and reflect the

Table 6-4

Atmospheric Emissions of 12-ounce Water Bottles
(g per 10,000 12-ounce water bottles)

	PLA (2005)	PET
Atmospheric Emissions		
dust (PM10)	2,128	553
CO	2,269	2,345
CO2	628,996	852,041
SOX as SO2	2,806	3,258
H2S	0.22	0.20
mercaptan	4.5E-04	0.20
NOX as NO2	3,721	2,182
NH3	1.27	0.32
Cl2	0.033	0.20
HCl	104	63.1
F2	2.1E-05	0.20
HF	4.19	2.25
hydrocarbons not specified elsewhere	433	1,757
aldehyde (-CHO)	0.48	0.44
organics	15.8	62.9
Pb+compounds as Pb	0.0020	0.20
Hg+compounds as Hg	3.9E-04	0.20
metals not specified elsewhere	0.18	0.61
H2SO4	0.0028	0.20
N2O	78.1	0.78
H2	63.8	75.1
dichloroethane (DCE) C2H4Cl2	4.2E-05	0.20
vinyl chloride monomer (VCM)	6.9E-04	0.20
CFC/HCFC/HFC not specified elsewhere	1.3E-06	0.20
organo-chlorine not specified elsewhere	2.10	0.20
HCN	0	0.20
CH4	4,015	4,695
aromatic HC not specified elsewhere	0.22	73.1
polycyclic hydrocarbons (PAH)	7.7E-05	1.42
NMVOC	77.4	253
CS2	0	0.20
methylene chloride CH2Cl2	0.0016	0.20
Cu+compounds as Cu	9.2E-05	0.20
As+compounds as As	0.0018	0.20
Cd+compounds as Cd	2.9E-04	0.20
Ag+compounds as Ag	0	0.20
Zn+compounds as Zn	4.7E-04	0.20
Cr+compounds as Cr	0.0012	0.81
Se+compounds as Se	0.0051	0.20
Ni+compounds as Ni	0.0076	1.42
Sb+compounds as Sb	1.3E-04	0.20

Table 6-4 (cont'd)

Atmospheric Emissions of 12-ounce Water Bottles
(g per 10,000 12-ounce water bottles)

	PLA (2005)	PET
Atmospheric Emissions		
ethylene oxide C2H4O	0	0.20
ethylene C2H4	0	0.41
oxygen	0	0.20
asbestos	0	0.20
dioxin/furan as Teq	3.6E-07	0.20
benzene C6H6	0.17	0.44
toluene C7H8	0.24	0.25
xylenes C8H10	0.14	0.23
ethylbenzene C8H10	0.018	0.21
styrene	4.6E-08	0.20
propylene	0.040	0.24
Fe+compounds as Fe	4.8E-04	0
Co+compounds as Co	8.3E-04	1.3E-04
V+compounds as V	0.0025	0
Al+compounds as Al	-0.87	0
B+compounds as B	0.0011	0
Manganese	0.0025	2.7E-04
Molybdenum	2.1E-05	0
Corn dust	15.8	0
Tin	1.1E-04	0
Titanium	2.1E-05	0
Barium	0.074	0
Beryllium	8.6E-05	4.1E-06
Bromine	8.8E-04	0
Cyanide (unspecified)	1.9E-04	1.8E-07
Fluoride (unspecified)	3.6E-04	1.3E-05
Helium	0.080	0
VOC (volatile organic compou	0.051	0
Dust (PM 2.5)	3.14	0
Dust (unspecified)	29.1	1.79
Ethanol	95.6	0
Lactic acid	0.18	0
Particles (< 2.5 um)	-4.39	0
Particles (> 10 um)	-53.7	0
Particles (<10 and > 2.5 um)	-48.0	0

Source: Franklin Associates, a Division of ERG

Table 6-5

Greenhouse Gas Summary for 12-ounce Water Bottles
(g carbon dioxide equivalents per 10,000 12-ounce water bottles)

	PLA (2005)	PET
CO2	628,996	852,041
N2O	23,128	231
CFC/HCFC/HFC not specified elsewhere	0.0022	345
CH4	92,351	107,976
methylene chloride CH2Cl2	0.016	2.03
Total	744,475	960,595

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, nitrous oxide--296, CFC/HCFCs--1700, methane--23, methylene chloride--10.

Source: Franklin Associates, a Division of ERG

ability of the many plants to identify specific emissions. For some emissions, it is possible to identify more specific emissions. For example, some specific metal ions are identified separately from the more general heading of metals. When such a split has been introduced, there is no double counting. For example, if a Na+ emission is identified, it is not included in the more general category of *metals (unspecified).* However, some operators may not necessarily have reported separately all of the metals specifically identified elsewhere in the table. As a consequence, the category *metals (unspecified)* may well include some metals that were specifically identified by other companies and are included under the appropriate specific heading elsewhere in the table."

Table 6-6 displays the individual waterborne emissions for each of the water bottle systems. It should be reiterated that a number of these emissions may be overstated due to the use of "1 mg" in place of the "<1 mg" given in the original PlasticsEurope datasets. This is not true of the PLA dataset, where precise amounts were given. No firm conclusions can be made from the various waterborne emissions that result from the water bottle systems.

CONCLUSIONS

A life cycle inventory (LCI) is an environmental profile that expresses environmental burdens from the perspective of energy consumption, solid waste generation, atmospheric emissions, and waterborne emissions. This LCI evaluated 12-ounce water bottle systems and found that three types of environmental burdens were helpful in distinguishing the LCI results: 1) energy requirements, 2) solid waste

generation, and 3) greenhouse gas emissions. The LCI conclusions for each of these categories are summarized below.

Energy Requirements

- The PET water bottle requires the most total energy; however, it total energy is not significantly different than the PLA 2005 total energy.
- If combustion energy credit is given, the net energy conclusions do *not* differ from the total energy conclusions regarding the PLA water bottles.
- The PET water bottles require more fossil fuel than the PLA water bottles. This is due in a large part to the feedstock energy of the PET water bottles.

Solid Waste Generation

- In many of the empirical solid waste categories, the solid waste amounts follow the trend of the energy, leading to the conclusion that these categories are dominated by fuel production and combustion solid waste.
- The PLA water bottle is the heaviest and so produces the more post consumer solid waste; however, there is only a three percent difference between the PLA and PET post consumer solid waste, and so they are not considered to be significantly different.

Greenhouse Gas Emissions

- The CO_2 equivalent amount for the PLA 2005 water bottles is significantly less than the CO_2 equivalent amount for the PET water bottles.

Table 6-6

Waterborne Emissions of 12-ounce Water Bottles
(g per 10,000 12-ounce water bottles)

	PLA (2005)	PET
Waterborne Wastes		
COD	1,245	245
BOD	228	407
Pb+compounds as Pb	0.027	0.22
Fe+compounds as Fe	10.6	3.88
Na+compounds as Na	646	262
acid as H+	0.28	1.22
NO3-	253	0.61
Hg+compounds as Hg	4.3E-05	0.20
ammonium compounds as NH4+	0.34	0.81
Cl-	2,087	817
CN-	1.1E-04	0.20
F-	0.85	0.20
S+sulphides as S	0.0021	0.20
dissolved organics (non-hydrocarbon)	0.11	3.45
suspended solids	810	146
detergent/oil	1.11	4.55
hydrocarbons not specified elsewhere	0.34	22.3
organo-chlorine not specified elsewhere	4.2E-04	0.20
dissolved chlorine	3.8E-04	0.20
phenols	0.026	0.21
dissolved solids not specified elsewhere	2,154	983
P+compounds as P	2.52	0.20
other nitrogen as N	17.7	0.41
other organics not specified elsewhere	0.20	61.0
SO4--	36.5	72.8
dichloroethane (DCE)	0	0.20
vinyl chloride monomer (VCM)	2.1E-05	0.20
K+compounds as K	0.26	0.20
Ca+compounds as Ca	182	68.9
Mg+compounds as Mg	30.6	13.6
Cr+compounds as Cr	0.11	0.26
ClO3--	0.013	0.20
BrO3--	6.3E-05	0.20

Table 6-6 (cont'd)

Waterborne Emissions of 12-ounce Water Bottles
(g per 10,000 12-ounce water bottles)

	PLA (2005)	PET
Waterborne Wastes		
TOC	329	8.33
AOX	4.2E-05	0.20
Al+compounds as Al	3.87	2.04
Zn+compounds as Zn	0.090	0.25
Cu+compounds as Cu	0.014	0.21
Ni+compounds as Ni	0.013	0.21
CO3--	0.055	16.4
As+compounds as As	0.013	0.21
Cd+compounds as Cd	0.0020	0.20
Mn+compounds as Mn	0.10	0.23
organo-tin as Sn	0	0.20
Ag+compounds as Ag	0.10	0.045
Ba+compounds Ba	52.7	25.2
Sr+compounds as Sr	2.64	1.37
V+compounds as V	0.0013	5.8E-04
organo-silicon	0	0.20
benzene	0.081	0.24
dioxin/furan as Teq	9.2E-06	0.20
Mo+compounds as Mo	0.0011	4.9E-04
Ca++	52.0	0
PO4(-3)	0.051	0
Chromium +III	0.0016	0
Chromium +IV	1.1E-04	0
Heavy metals unspecified	7.60	1.19
Selenium	0.0013	2.6E-04
Titanium	0.037	0.018
Chlorine dissolved	0.0011	0
Fluorine	2.5E-04	0
Neutral salts	0.0054	0
halogenated organics	0.016	6.1E-05

Source: Franklin Associates, a Division of ERG

APPENDIX A

CORN GRAIN AGRICULTURAL DATA

INTRODUCTION

This appendix is a brief analysis of the data on corn growing as reported in Vink (Reference A-1). The energy values presented by Vink are compared to those reported by USDA (Reference A-2). The USDA database uses primary data gathered by extensive surveying of U.S. corn growers and users and is likely the most reliable source of information on this subject. The co-product allocation among corn grain and corn fodder is also discussed.

COMPARISON

The agricultural data in Vink's study is based on a functional unit of the quantity of corn required for the manufacture of 1.00 kilogram of PLA resin at the plant gate. The fossil energy for the functional unit is 3.8 MJ for operating supplies and 1.1 MJ for electricity and fuels used on the farm (Reference A-1, p. 412, for a total of 4.9 MJ.

NatureWorks says that 2.5 kg of corn grain (15% moisture) is needed to manufacture 1.00 kg of PLA (Reference A-4). The excess 1.5 kg mass is not waste, but is water and co-products of the corn wet mill. According to NatureWorks (Reference A-4), the average composition of corn is listed as 66.12% starch and 1.84% sugars. These components, which account for 68.0% of the corn grain, are the components that potentially can be used to make PLA. The weight of corn grain input per 1.00 kilogram of PLA is thus 1.70 kilograms (68% x 2.5 kg = 1.70 kg).

USDA reports total energy inputs of 57,476 Btu/bushel (60.6 MJ/bushel) to grow and haul corn (Reference A-2, Table 4). There are 56 lbs (25.4 kg) of corn per bushel; therefore the energy requirements for corn growing are 2.37 MJ/kg of corn grain. If 1.7 kg of corn is needed to make 1.0 kg of PLA, the energy requirement would be 4.03 MJ (1.7 kg X 2.37 MJ/kg = 4.03 MJ). The Vink energy requirements for growing corn for 1.00 kg of PLA are 4.9 MJ/kg, which is 22 percent higher than the USDA value ((4.9-4.03)/4.03).

In the above analysis the energy value in Vink (Reference A-1) appears slightly higher than the USDA value (Reference A-2), but the error bars on this comparison are much larger than the difference; as a result, there is no basis for considering the two results to be different. Several reasons for making this statement follow.

1. The USDA and Vink studies use different data sources. The corn growing data in Vink (Reference A-1) is from the Boustead database (Reference A-3). We have requested more detail from Boustead, but so far have not received it. Vink states that the corn growing data is from four to five

states, while the USDA data is from nine states in the same Upper Midwest region. However, North Dakota is included in Vink, but not included in USDA, and Iowa (usually the leading corn grain producing state) is included in USDA but not in Vink. USDA shows that there are large differences in yields, application of nitrogen fertilizers and energy data from state to state. Each of these has a significant effect on results.

2. In the USDA analysis, the manufacture of nitrogen fertilizer accounts for 33 percent of the total agricultural energy (Reference A-2, Table 4). The energy for nitrogen fertilizer production varies by a factor of almost two between various states. Both Vink (Reference A-1) and USDA (Reference A-2) use nitrogen fertilizer manufacturing data from external databases. The fertilizer production data from these databases may or may not be comparable. Thus, the agricultural data for the two studies is based on not only a different set of corn-growing states, but also different databases used for the dominant energy-consuming step.

3. The energy comparison above is based on 1.7 kg of corn needed to produce 1.00 kg of PLA. This factor was derived by combining two different data sources with no high level of confidence of comparability. Thus, this important factor may be in error. The actual value likely lies somewhere between 1.00 and 2.5; 1.7 is only an estimate.

CO-PRODUCT ALLOCATION

A methodological issue that can have large impacts on results and conclusions is co-product allocation. Corn growing produces corn grain and corn fodder (primarily stalks and leaves). The amount of fodder produced is highly variable, but the number of kilograms of fodder and grain are often about the same. Corn plants may be harvested for grain or for silage (animal feed). When corn is cut for silage, a high moisture content is desired, so the corn is harvested while the plant is mostly green and the grain is not fully ripened. On the other hand, when corn is harvested for grain, the plant is allowed to reach full maturity. At this stage the stalks and leaves are much drier and less satisfactory as animal feed and are generally left in the field. Thus, as a practical matter, there is little basis for considering fodder as a co-product when grain harvesting is the primary goal. (Fodder is considered here only for potential co-product use as animal feed. No other potential uses of fodder were considered.).

Hosein Shapouri (Reference A-5) makes it clear that the USDA data assign all energy to the corn grain. While Vink does not clearly define whether any allocation is used, their data seems to correspond reasonably well with the USDA data, which suggests that no co-product allocation was done, or that any allocation that was done did not have a significant effect on results.

CONCLUSION

Based upon the information available, the corn growing data in Vink, drawn from the Boustead database, appears consistent with the extensively peer reviewed and widely accepted USDA database.

REFERENCES

A-1 Vink, Erwin T. H., Karl Rabago, David Glassner and Patrick Gruber, **Applications of life cycle assessment to NatureWorks polylactide (PLA) production,** Polymer Degradation and Stability, 80 (2003) 403-419. (Abbreviated as Vink.)

A-2 Shapouri, Hosein, James Duffield and Michael Wang, **The energy balance of corn ethanol: an update,** U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses, Agricultural Economic Report No. 813 (2002.) (Abbreviated as USDA.)

A-3 Email: from Erwin Vink to Bill Franklin, Jan 19, 2005.

A-4 NatureWorks Website: http://www.natureworksllc.com/rightnow/index.asp

A-5 Email: from Hosein Shapouri to Bob Hunt, June 19, 2006.

APPENDIX B

STUDY APPROACH AND METHODOLOGY

LIFE CYCLE INVENTORY METHODOLOGY

Key elements of the LCI methodology include the study boundaries, resource inventory (raw materials and energy), and emissions inventory (atmospheric, waterborne, and solid waste). Although much of the data used in this report comes from Boustead Consulting and from NatureWorks, LLC, some processes are modeled and presented by Franklin Associates. The methodology used by Boustead Consulting for the PlasticsEurope database can be downloaded at http://www.lca.plasticseurope.org/main2.htm. Dr. Erwin Vink states in his journal paper that he uses this same methodology. The Franklin Associates LCI methodology is described below.

Franklin Associates developed a methodology in the 1970s for performing resource and environmental profile analyses (REPA), commonly called life cycle inventories. This methodology has been documented for the U.S. Environmental Protection Agency and is incorporated in the 1992 EPA report **Product Life-Cycle Assessment Inventory Guidelines and Principles.** The methodology is also consistent with the life cycle inventory methodology described in the current ISO 14040 standards:

- ISO 14040 Environmental Management—Life Cycle Assessment—Principles and Framework. Reference No. ISO 14040:1997(E)
- ISO 14041 Environmental Management—Life Cycle Assessment—Goal and Scope Definition and Inventory Analysis. Reference No. 14041:1998(E)
- ISO 14043 Environmental Management—Life Cycle Assessment—Life Cycle Interpretation. Reference No. 14043:2000(E).

Much of the data presented in this report were developed using this methodology, which has been in use for over 35 years.

Figure B-1 illustrates the basic approach to data development for each major process in an LCI analysis. This approach provides the essential building blocks of data used to construct a complete resource and environmental emissions inventory profile for the entire life cycle of a product. Using this approach, each individual process included in the study is examined as a closed system, or "black box", by fully accounting for all resource inputs and process outputs associated with that particular process. Resource inputs accounted for in the LCI include raw materials and energy use, while process outputs accounted for include products manufactured and environmental emissions to land, air, and water.

For each process included in the study, resource requirements and environmental emissions are determined and expressed in terms of a standard unit of output. A standard unit of output is used as the basis for determining the total life cycle resource requirements and environmental emissions of a product.

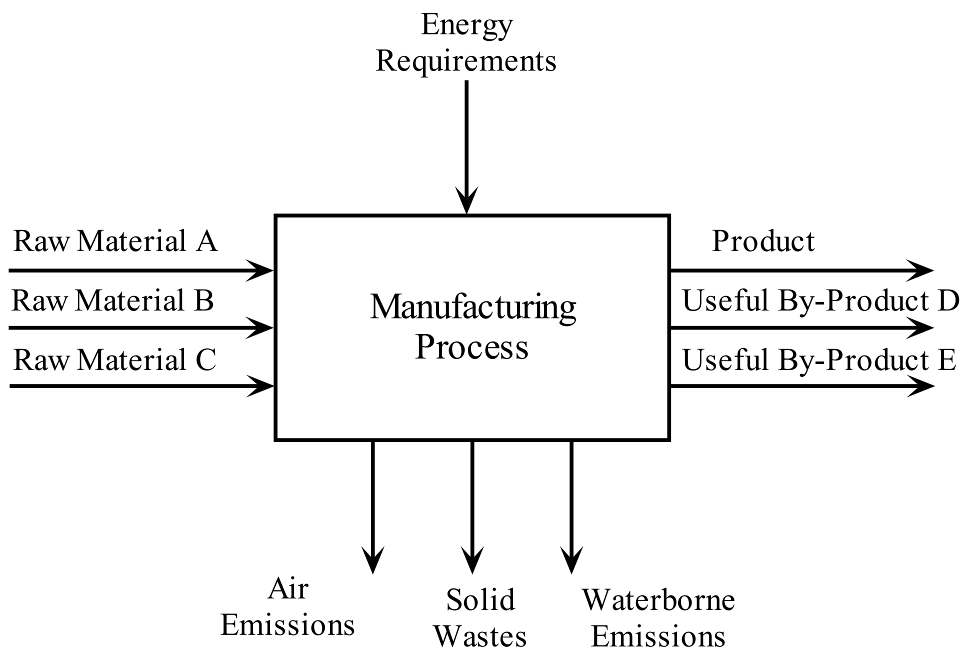

Figure B-1. "Black box" concept for developing LCI data

Material Requirements

Once the LCI study boundaries have been defined and the individual processes identified, a material balance is performed for each individual process. This analysis identifies and quantifies the input raw materials required per standard unit of output, such as 1 kilogram, for each individual process included in the LCI. The purpose of the material balance is to determine the appropriate weight factors used in calculating the total energy requirements and environmental emissions associated with the materials used. Energy requirements and environmental emissions are determined for each process and expressed in terms of the standard unit of output.

Once the detailed material balance has been established for a standard unit of output for each process included in the LCI, a comprehensive material balance for the entire life cycle of each product system is constructed. This analysis determines the quantity of materials required from each process to produce and dispose of the required quantity of each system component and is typically illustrated as a flow chart. Data must be gathered for each process shown in the flow diagram, and the weight relationships of inputs and outputs for the various processes must be developed.

Energy Requirements

The average energy requirements for each process identified in the LCI are first quantified in terms of fuel or electricity units, such as cubic meters of natural gas, liters of diesel fuel, or kilowatt-hours (kWh) of electricity. The fuel used to transport raw materials to each process is included as a part of the LCI energy requirements. Transportation energy requirements for each step in the life cycle are developed in the conventional units of tonne-kilometers by each transport mode (e.g,. truck, rail, barge, etc.). Statistical data for the average efficiency of each transportation mode are used to convert from tonne-kilometers to fuel consumption.

Once the fuel consumption for each industrial process and transportation step is quantified, the fuel units are converted from their original units to an equivalent Btu value based on standard conversion factors.

The conversion factors have been developed to account for the energy required to extract, transport, and process the fuels and to account for the energy content of the fuels. The energy to extract, transport, and process fuels into a usable form is labeled precombustion energy. For electricity, precombustion energy calculations include adjustments for the average efficiency of conversion of fuel to electricity.

The LCI methodology assigns a fuel-energy equivalent to raw materials that are derived from fossil fuels. Therefore, the total energy requirement for coal, natural gas, or petroleum-based materials includes the fuel-energy of the raw material (called energy of material resource or feedstock energy). In this study, this applies to the crude oil and natural gas used to produce the plastic resins. The NatureWorks LCI of PLA does give a feedstock energy value to the corn used as a raw material in PLA. Franklin Associates does not commonly assign a fuel-energy equivalent to combustible materials, such as corn, that are not major fuel sources in this country.

Environmental Emissions

Environmental emissions are categorized as atmospheric emissions, waterborne wastes, and solid wastes, and represent discharges into the environment after the effluents pass through existing emission control devices. Similar to energy, environmental emissions associated with processing fuels into usable forms (precombustion emissions) are also included in the inventory. When it is not possible to obtain actual industry emissions data, published emissions standards are used as the basis for determining environmental emissions.

The different categories of atmospheric and waterborne emissions are not totaled in this LCI because it is widely recognized that various substances emitted to air and water differ greatly in their effect on the environment.

Atmospheric Emissions. These emissions include substances classified by regulatory agencies as pollutants, as well as selected nonregulated emissions such as carbon dioxide. For each process, atmospheric emissions associated with the combustion of fuel for process or transportation energy, as well as any emissions released from the process itself, are included in this LCI. Emissions are reported as grams of pollutant per the basis of each product. The amounts reported represent actual discharges into the atmosphere after the emissions pass through existing emission control devices. Some of the more commonly reported atmospheric emissions are carbon dioxide, carbon monoxide, non-methane hydrocarbons, nitrogen oxides, particulates, and sulfur oxides.

Waterborne Wastes. As with atmospheric emissions, waterborne wastes include all substances classified as pollutants. Waterborne wastes are reported as grams of pollutant per the basis of each product. The values reported are the average quantity of pollutants still present in the wastewater stream after wastewater treatment and represent discharges into receiving waters. This includes both process-related and fuel-related waterborne wastes. Some of the most commonly reported waterborne wastes are acid, ammonia, biochemical oxygen demand (BOD), chemical oxygen demand (COD), chromium, dissolved solids, iron, and suspended solids.

Solid Wastes. This category includes solid wastes generated from all sources that are landfilled or disposed in some other way. This also includes materials that are burned to ash at combustion facilities. It does not include materials that are recycled or co-products. When a product is evaluated on an environmental basis, attention is often focused on post consumer wastes. Industrial wastes generated during the manufacture of the product are sometimes overlooked. Industrial solid wastes include wastewater treatment sludges, solids collected in air pollution control devices, trim or waste materials from manufacturing operations that are not recycled, fuel combustion residues such as the ash generated by burning coal or wood, and mineral extraction wastes. Waste materials that are left on-site or diverted from landfill and returned to the land without treatment (e.g., overburden returned to mine site, cornstalks returned to the field or forest residues left in the forest to decompose) are not reported as wastes.

DATA

The accuracy of the study is only as good as the quality of input data. The development of methodology for the collection of data is essential to obtaining quality data. Careful adherence to that methodology determines not only data quality but also objectivity. Franklin Associates has developed a methodology for incorporating data quality and uncertainty into LCI calculations. Data quality and uncertainty are discussed in more detail at the end of this section.

Data necessary for conducting this analysis are separated into two categories: process-related data and fuel-related data.

Process Data

No primary process data were actually collected from manufacturers in this analysis. The PlasticsEurope LCI database and NatureWorks' LCI data were used for the plastic resins and fabrications processes. The PlasticsEurope methodology report explains the process data collection methodology used by Boustead Consulting. Dr. Erwin Vink's 2006 journal article also gives a short explanation about data collection for the PLA resin.

Data Sources. The results of this study are based on available public data. Only PLA drying, transportation, and disposal data were developed specifically for this project. Data for the production of the PLA resin were taken from Dr. Vink's journal article featuring LCI data as performed by NatureWorks in 2006. Data for the production of the other plastic resins (PET, HIPS, GPPS, PP) and the fabrication processes were taken from the PlasticsEurope database. The drying data for the PLA resin were estimated from specification on the ConAir dehumidifying dryer, CD1600. Transportation from the resin producer to the product fabrication was estimated using average distances between various locations of actual U.S. resin plants and product fabrication plants.

Fuel Data

When fuels are used for process or transportation energy, there are energy and emissions associated with the production and delivery of the fuels as well as the energy and emissions released when the fuels are burned. Before each fuel is usable, it must be mined, as in the case of coal or uranium, or extracted from the earth in some manner. Further processing is often necessary before the fuel is usable. For example, coal is crushed or pulverized and sometimes cleaned. Crude oil is refined to produce fuel oils, and "wet" natural gas is processed to produce natural gas liquids for fuel or feedstock.

To distinguish between environmental emissions from the combustion of fuels and emissions associated with the production of fuels, different terms are used to describe the different emissions. The combustion products of fuels are defined as "combustion data." Energy consumption and emissions that result from the mining, refining, and transportation of fuels are defined as "precombustion data." Precombustion data and combustion data together are referred to as "fuel-related data."

Fuel-related data are developed for fuels that are burned directly in industrial furnaces, boilers, and transport vehicles. Fuel-related data are also developed for the production of electricity. These data are assembled into a model from which the energy requirements and environmental emissions for the production and combustion of process fuels are calculated.

Energy data are developed in the form of units of each primary fuel required per unit of each fuel type. For electricity production, federal government statistical records provided data for the amount of fuel required to produce electricity from each fuel source, and the total amount of electricity generated from petroleum, natural gas, coal, nuclear, hydropower, and other (solar, geothermal, etc.). Literature sources and U.S. federal government statistical records provided data for the emissions resulting from the combustion of fuels in utility boilers, industrial boilers, stationary equipment such as pumps and compressors, and transportation equipment. Because electricity is required to produce primary fuels, which are in turn used to generate electricity, a circular loop is created. Iteration techniques are utilized to resolve this loop.

In 2003, Franklin Associates updated its fuels and energy database for inclusion in the U.S. LCI Database <www.nrel.gov/lci>. The fuels and energy modules in that database are used only for the drying of PLA, transporting of resins to fabrication, and disposal of products. There are some differences between the Franklin Associates fuels database and the Boustead model, the fuel database used by PlasticsEurope and NatureWorks. Electricity delivery losses are handled differently, as well as the different data sources.

Data Quality Goals for This Study

ISO standards 14040, 14041 and 14043 each detail various aspects of data quality and data quality analysis. ISO 14041 Section 5.3.6 states: "Descriptions of data quality are important to understand the reliability of the study results and properly interpret the outcome of the study." The section goes on to list three critical data quality requirements: time-related coverage, geographical coverage, and technology coverage. Additional data quality descriptors that should be considered include whether primary or secondary data were used and whether the data were measured, calculated, or estimated.

The data quality goal for this study is to use the best publicly available and most representative data for the materials used and processes performed in terms of time, geographic, and technology coverage.

In some cases, it was possible to achieve the intended data quality goals of the study in terms of current public data and geographic and technology coverage. The transport of resin to fabrication, drying of PLA, and disposal datasets satisfy the goal as they are current U.S. datasets. The PlasticsEurope database represents current European resin and fabrication processes. Dr. Vink's 2006 journal paper states that Boustead Consulting's model was used for the PLA LCI, using the MAPP U.S. regional grid for electricity. Detailed data quality information can be found in Appendix C of this report.

All Franklin Associates' fuel data were reviewed and extensively updated in 2003 for the U.S. Electricity fuel sources and generation do meet all the data quality goals.

Data Accuracy

An important issue to consider when using LCI study results is the reliability of the data. In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a complex subject, and one that does not lend itself to standard error analysis techniques. Techniques such as Monte Carlo analysis can be used to study uncertainty, but the greatest challenge is the lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates. However, the reliability of the study can be assessed in other ways.

A key question is whether the LCI profiles are accurate and study conclusions are correct. It is important that the environmental profiles accurately reflect the relative magnitude of energy requirements and other environmental burdens for the various materials analyzed.

The accuracy of an environmental profile depends on the accuracy of the numbers that are combined to arrive at that conclusion. Because of the many processes required to produce the products analyzed in this study, many numbers in the LCI are added together for a total numeric result. Each number by itself may contribute little to the total, so the accuracy of each number by itself has a small effect on the overall accuracy of the total. There is no widely accepted analytical method for assessing the accuracy of each number with any degree of confidence.

There are several other important points with regard to data accuracy. Each number generally contributes a small part to the total value, so a large error in one data point does not necessarily create a problem. For process steps that make a larger than average contribution to the total, special care is taken with the data quality. It is assumed that with careful scrutiny of the data, any errors will be random. That is, some numbers will be a little high due to errors, and some will be slightly low, but in the summing process these random high and low errors will offset each other to some extent.

There is another dimension to the reliability of the data. Certain numbers do not stand alone, but rather affect several numbers in the system. An example is the amount of a raw material required for a process. This number will affect every step in the production sequence prior to the process. Errors such as this that propagate throughout the system are more significant in steps that are closest to the end of the production sequence. For example, changing the weight of an input to the fabrication of a product changes the amounts of the inputs to that process, and so on back to the quantities of raw materials.

In summary, for the particular data sources used and for the specific methodology described in this report, the results of this report are believed to be as accurate and reasonable as possible.

CRITICAL/PEER REVIEW

Critical review is specified in ISO standard 14040 as an optional component for LCI/LCA studies. The purpose is to verify that the study has met the requirements of the international standards for methodology, data and reporting. The review may be conducted by internal experts other than the persons performing the study, external experts, or by a review panel of interested parties.

Franklin Associates LCA staff has reviewed unit process data, eco-profiles, models, and cradle-to-grave results internally. The study is also submitted to the client for critical review. Because this study uses all public data sources, most of which has been reviewed by other sources, no further review by external interested parties is planned, but could be conducted at a later time if the client wishes to do so.

METHODOLOGY ISSUES

The following sections discuss how several key methodological issues are handled in this study.

Integration of Results to PlasticsEurope Energy and Emissions Categories

Due to the fact that a large portion of the data used in this report comes from PlasticsEurope, Franklin Associates used the energy, solid waste, and emissions categories as reported in the PlasticsEurope Eco-Profiles.

The PlasticsEurope Eco-Profiles use four categories to present energy requirements: energy content of delivered fuel, transport energy, feedstock energy, and fuel production and delivery energy. The following definitions are quotes from the Methodology report for the PlasticsEurope database. "*Energy content of delivered fuel* represents the energy that is received by the final operator who consumes energy. *Feedstock energy* represents the energy of the fuel bearing materials that are taken into the system but used as materials rather than fuels. *Transport energy* refers to the energy associated with fuels consumed directly by the transport operations as well as any energy associated with the production of non- fuel bearing materials, such as steel, that are taken into the transport process. *Fuel production and delivery energy* represents the energy that is used by the fuel producing industries in extracting the primary fuel from the earth, processing it and delivering it to the ultimate consumer."

Franklin Associates commonly uses three categories to present energy requirements: process energy, transportation energy, and energy of material resource. The "fuel production and delivery energy" used by PlasticsEurope is usually contained within Franklin Associates' process and transportation energy categories. Franklin Associates considers this energy to be precombustion energy in our terms. In this analysis, Franklin Associates separated out the precombustion energy to be included as fuel production and delivery energy. Process energy is included in energy content of delivered fuel.

Transportation energy is included in transport energy. Energy of material resource is included in feedstock energy.

Franklin Associates does not commonly include solid waste that is not actually *disposed* of in a type of landfill. The PlasticsEurope Eco-Profiles uses an empirical system of reporting solid waste, which identifies the type of waste that is *generated.* This system includes some solid waste that Franklin Associates would not normally include as solid waste, such as waste to incinerator, waste returned to mine, and tailings. The portions of this study that Franklin Associates modeled did not include any industrial solid waste. All solid wastes from the Franklin Associates models were from the fuels. These solid wastes were included in the category of slags and ash. A category for post consumer solid waste was also added to the PlasticsEurope solid waste categories list.

Franklin Associates used the PlasticsEurope and NatureWorks list of atmospheric and waterborne emissions to limit the fuels database available. The Franklin Associates fuels database has almost 200 emissions in it. To keep the fuel data sources comparable, Franklin Associates pared down our fuels database to match the PlasticsEurope fuels data list.

Electricity Grid Fuel Profile

In general, detailed data do not exist on the fuels used to generate the electricity consumed by each industry. Electricity production and distribution systems in the United States are interlinked and are not easily separated. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid. Therefore, the U.S. average fuel consumption by electrical utilities is assumed in the Franklin Associates model.

Electricity generated on-site at a manufacturing facility is represented in the process data by the fuels used to produce it. A portion of on-site generated electricity is sold to the electricity grid. This portion is accounted for in the calculations for the fuel mix in the grid.

System Components Not Included

Unless otherwise stated in the PlasticsEurope methodology paper, the following components of each system are not included in this LCI study.

Capital Equipment. The energy and wastes associated with the manufacture of capital equipment are not included. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery. The energy and emissions associated with such capital equipment generally, for 1,000 pounds of materials, become negligible when averaged over the millions of pounds of product manufactured over the useful lifetime of the capital equipment.

Space Conditioning. The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations in most cases. For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. Energy consumed for space conditioning is usually less than one percent of the total energy consumption for the manufacturing process. This assumption has been checked in the past by Franklin Associates staff using confidential data from manufacturing plants.

Support Personnel Requirements. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

Miscellaneous Materials and Additives. Selected materials such as catalysts, pigments, or other additives, which total less than one percent by weight of the net process inputs, are not included in the assessment. Omitting miscellaneous materials and additives helps keep the scope of the study focused and manageable within budget and time constraints. Additives such as plasticizers, stabilizers, etc. added to resins to adapt them for specific product applications were not included.

APPENDIX C

DATA QUALITY

This data quality chapter evaluates the representativeness of the data in the study, which is defined by ISO to be a qualitative assessment of degree to which the dataset reflects the true population of interest (ISO 14041, Section 5.3.6).

The following fall under data representativeness:

- time/temporal coverage – describes the age of data and the minimum length of time (e.g., one year) over which data should be collected;
- geographical coverage – describes the geographical area from which data for unit processes are collected to satisfy the goal of the study; and
- technological coverage (or the technology mix) – this may include weighted average of the actual process mix, best available technology, or worst operating unit.

The data quality goal for this study is to use the best publicly available and most representative data for the materials used and processes performed in terms of time, geographic, and technology coverage.

In some cases, it was possible to achieve the intended data quality goals of the study in terms of current public data and geographic and technology coverage. The transport of resin to fabrication, drying of PLA, and disposal datasets satisfy the goal as they are current U.S. datasets. The PlasticsEurope database represents current European resin and fabrication processes. Dr. Vink's 2006 journal paper states that Boustead Consulting's model was used for the PLA LCI, using the MAPP U.S. regional grid for electricity. All Franklin Associates' fuel data were reviewed and extensively updated in 2003 for the U.S. Electricity fuel sources and generation do meet all the data quality goals.

Table C-1 presents the temporal, technological, and geographical coverage for this LCI.

Table C-1. Temporal, Technological, and Geographical Coverage

	Data Quality Indicators and Comments				
	Type of data	**Temporal information**	**Technological coverage**	**Geographical coverage of data**	**Source of data**
Petroleum-based Resin data	Primary from a public source	All resin data used was updated in 2005.	Current technologies for each resin	EU average	PlasticsEurope database produced by Boustead Consulting
PLA Resin data	Primary from one private industry source	Resin data were updated in 2005	Current PLA technology	U.S. using MAPP electricity grid	NatureWorks, LLC, Dr. Erwin Vink's 2006 journal paper
Fabrication data (thermoforming, film extrusion, blow-molding)	Primary from a public source	Fabrication data collected 1996	Narrow number of plants: thermoforming (3), film extrusion (1), stretch blow-molding (1)	EU	PlasticsEurope database produced by Boustead Consulting
Transport of resin to fabrication	Transportation distances were estimated using representative current resin producer facilities and fabricator locations	Estimated in 2006	Current mobile equipment	U.S.	MapQuest, Information from APC's Plastics database on resin locations. Information from web searches on major cup, deli container, envelope window film, foam meat trays, and water bottle producers.
Disposal	Primary and secondary sources	Landfill & combustion information last updated 2003	Current U.S. technology	U.S.	Information from a midwest U.S. waste management company. **Municipal Solid Waste in the United States: 2001 Facts and Figures.** EPA530-R-03-011, October 2003.

APPENDIX D

CONSIDERATIONS FOR INTERPRETATION OF DATA AND RESULTS

INTRODUCTION

An important issue with LCI results is whether two numbers are really different from one another. For example, if one product has a total system requirement of 100 energy units, is it really different from another product system that requires 110 energy units? If the error or variability in the data is sufficiently large, it cannot be concluded that the two numbers are actually different.

STATISTICAL CONSIDERATIONS

A statistical analysis that yields clear numerical answers would be ideal, but unfortunately LCI data are not amenable to this. The data are not (1) random samples from (2) large populations that result in (3) "normal curve" distributions. LCI data meet none of these requirements for statistical analysis. LCI data for a given sub-process (such as potato production, roundwood harvesting, or caustic soda manufacture, for example) are generally selected to be representative of a process or industry, and are typically calculated as an average of two to five data points. In statistical terminology, these are not random samples, but "judgment samples," selected so as to reduce the possible errors incurred by limited sampling or limited population sizes. Formal statistics cannot be applied to judgment samples; however, a hypothetical data framework can be constructed to help assess in a general sense the reliability of LCI results.

The first step in this assessment is reporting standard deviation values from LCI data, calculated by,

$$s = \sqrt{\frac{\sum (x_1 - x_{mean})^2}{n-1}},$$

where x_i is a measured value in the data set and x_{mean} is the average of n values. An analysis of sub-process data from Franklin Associates, Ltd. files shows that, for a typical sub-process with two to five different companies supplying information, the standard deviation of the sample is about 30 percent of the sample average.

In a typical LCI study, the total energy of a product system consists of the sum of many sub-processes. For the moment, consider an example of adding only two numbers. If both numbers are independent of each other and are an average of measurements which have a sample standard deviation, s, of 30, the standard deviation of the sum is obtained by adding the variances of each term to form the sum of the variances, then taking the square root. Variances are calculated by squaring the standard deviation, s^2, so the sum of

the variances is $30^2 + 30^2 = 900 + 900 = 1800$. The new standard deviation of the sum is the square root of the sum of the variances, or $\sqrt{1800} = 42.4$. In this example, suppose both average values are 100, with a sum of 200. If reported as a percent of the sum, the new standard deviation is 42.4/200 = 21.3% of the sum. Another way of obtaining this value is to use the formula $s_{\%} = \frac{s/x_{mean}}{\sqrt{n}}$, where the term $s_{\%}$ is defined as the standard deviation of n data points, expressed as a percentage of the average, where each entry has approximately the same standard deviation, s. For the example, then, $s_{\%} = \frac{30\%}{\sqrt{2}} =$ 21.3%.

Going back to a hypothetical LCI example, consider a common product system consisting of a sum of approximately 40 subsystems. First, a special hypothetical case is examined where *all of the values are approximately the same size, and all have a standard deviation of 30%.* The standard deviation in the result is $s_{\%} = \frac{30\%}{\sqrt{40}} = 4.7\%$. The act of summing reduces the standard deviation of the result with respect to the standard deviation of each entry because of the assumption that errors are randomly distributed, and by combining values there is some cancellation of total error because some data values in each component system are higher than the true values and some are lower.

The point of this analysis, however, is to compare two results, e.g., the energy totals for two different product systems, and decide if the difference between them is significant or not. To test a hypothetical data set it will be assumed that two product systems consist of a sum of 40 values, and that the standard deviation, $s_{\%}$, is 4.7% for each product system.

If there is statistical knowledge of the sample only, and not of the populations from which they were drawn, "t" statistics can be used to find if the two product totals are different or not. The expression selected is:
$\mu 1 - \mu 2 = x1 - x2 +/- t_{.025} s' \sqrt{\frac{1}{n1} + \frac{1}{n2}}$, where $\mu 1 - \mu 2$ is the difference in population means, x_1-x_2 is the difference in sample means, and s' is a pooled standard deviation of the two samples. For the hypothetical case, where it is assumed that the standard deviation of the two samples is the same, the pooled value is simply replaced with the standard deviation of the samples.

The goal is to find an expression that compares our sample means to "true," or population, means. A new quantity is defined:
$\Delta = (\mu 1 - \mu 2) - (x1 - x2)$, and the sample sizes are assumed to be the same (i.e., n_1=n_2).
The result is $\Delta = t_{.025} s' \sqrt{\frac{2}{n}}$, where Δ is the minimum difference corresponding to a 95%

confidence level, s' is the standard deviation of the sum of n values, and $t_{.025}$ is a t statistic for 95% confidence levels. The values for t are a function of n and are found in tables. This expression can be converted to percent notation by dividing both sides by the average of the sample means, which results in $\Delta\% = t_{.025} s'\% \sqrt{\frac{2}{n}}$, where $\Delta\%$ is now the percent difference corresponding to a 95% confidence level, and s'% is the standard deviation expressed as a percent of the average of the sample means. This formula can be simplified for the example calculation by remembering that $s'\% = \frac{s\%}{\sqrt{n}}$, where s% is the standard deviation of each energy entry for a product system. Now the equation becomes $\Delta\% = t_{.025} s\% \frac{\sqrt{2}}{n}$. For the example, t = 2.0, s = 30%, and n = 40, so that $\Delta\%$ = 2.1%. This means that if the two product system energy totals differ by more than 2.1%, there is a 95% confidence level that the difference is significant. That is, if 100 independent studies were conducted (in which new data samples were drawn from the same population and the study was conducted in the identical manner), then 95 of these studies would find the energy values for the two product systems to differ by more than 2.1%.

The previous discussion applies only to a hypothetical and highly idealized framework to which statistical mathematics apply. LCI data differ from this in some important ways. One is that the 40 or so numbers that are added together for a final energy value of a product system are of widely varying size and have different variances. The importance of this is that large numbers contribute more to the total variance of the result. For example, if 20 energy units and 2,000 energy units are added, the sum is 2,020 energy units. If the standard deviation of the smaller value is 30% (or 6 units), the variance is $6^2 = 36$. If the standard deviation of the larger number is 10% (or 200), the variance is $200^2 = 40{,}000$. The total variance of the sum is 36 + 40,000 = 40,036, leading to a standard deviation in the sum of $\frac{\sqrt{(40036)}}{2020}$ = 9.9%. Clearly, the variance in the result is much more greatly influenced by larger numbers. In a set of LCI energy data, standard deviations may range from 10% to 60%. If a large number has a large percentage standard deviation, then the sum will also be more uncertain. If the variance of the large number is small, the answer will be more certain. To offset the potential problem of a large variance, Franklin Associates goes to great lengths to increase the reliability of the larger numbers, but there may simply be inherent variability in some numbers which is beyond the researchers' control.

If only a few numbers contribute most of the total energy in a system, the value of $\Delta\%$ goes up. This can be illustrated by going back to the formula for $\Delta\%$ and calculating examples for n = 5 and 10. From statistical tables, the values for $t_{.025}$ are 2.78 for n = 5, and 2.26 for n = 10. Referring back to the hypothetical two-product data set with s% = 30% *for each entry*, the corresponding values for $\Delta\%$ are 24% for n = 5 and 9.6% for n = 10. Thus, if only five numbers out of 40 contribute most of the energy,

the percent *difference* in the two product system energy values must increase to 24% to achieve the 95% confidence level that the two values are different. The minimum difference decreases to 9.6% if there are 10 major contributors out of the 40 energy numbers in a product system.

CONCLUSIONS

The discussion above highlights the importance of sample size, and of the variability of the sample. However, once again it must be emphasized that the statistical analysis does not apply to LCI data. It only serves to illustrate the important issues. Valid standard deviations cannot be calculated because of the failure of the data to meet the required statistical formula assumptions. Nevertheless, it is important to achieve a maximum sample size with minimum variability in the data. Franklin Associates examines the data, identifies the large values contributing to a sum, then conducts more intensive analysis of those values. This has the effect of increasing the number of data points, and therefore decreasing the "standard deviation." Even though a calculated standard deviation of 30% may be typical for Franklin Associates' LCI data, the actual confidence level is much higher for the large values that control the variability of the data than for the small values. However, none of this can be quantified to the satisfaction of a statistician who draws conclusions based upon random sampling. In the case of LCI data, it comes down to a matter of professional judgment and experience. The increase in confidence level resulting from judgment and experience is not measurable.

It is the professional judgment of Franklin Associates, based upon over 25 years of experience in analyzing LCI data, that a 10% rule is a reasonable value for $\Delta\%$ for stating results of product system energy totals. That is, if the energy of one system is 10% different from another, it can be concluded that the difference is significant. It is clear that this convention is a matter of judgment. This is not claimed to be a highly accurate statement; however, the statistical arguments with hypothetical, but similar, data lend plausibility to this convention.

We also conclude that the weight of post consumer solid waste data can be analyzed in a similar way. These data are at least as accurate as the energy data, perhaps with even less uncertainty in the results. Therefore, the 10% rule applies to post consumer solid waste weight. However, we apply a 25% rule to the solid waste volume data because of greater potential variability in the volume conversion factors.

Air and water pollution and industrial solid waste data are not included in the 10% rule. Their variability is much higher. Data reported by similar plants may differ by a factor of two, or even a factor of 10 or higher in some cases. Standard deviations may be as high as 150%, although 75% is typical. This translates to a hypothetical standard deviation in a final result of 12%, or a difference of at least 25% being required for a 95% confidence of two totals being different if 10 subsystems are major contributors to the final results. However, this rule applies only to single emission categories, and cannot be extended to general statements about environmental emissions resulting from a single product system. The interpretation of environmental emission data is further complicated

by the fact that not all plants report the same emission categories, and that there is not an accepted method of evaluating the relative importance of various emissions.

It is the intent of this appendix to convey an explanation of Franklin Associates' 10% and 25% rules and establish their plausibility. **Franklin Associates' policy is to consider product system totals for energy and weight of post consumer solid waste weight to be different if there is at least a 10% difference in the totals. Otherwise, the difference is considered to be insignificant. In the detailed tables of this report there are many specific pollutant categories that are variable between systems. For the air and waterborne emissions, industrial solid waste, and post consumer solid waste volume, the 25% rule should be applied.** The formula used to calculate the difference between two systems is:

$$\% \text{ Diff} = \left(\frac{x-y}{\frac{x+y}{2}} \right) \text{ X } 100,$$

where x and y are the summed totals of energy or waste for two product systems. The denominator of this expression is the average of the two values.